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# The Enduring Nuclear Fuel Cycle

**Edited by:**
**Carl E. Walter**

***Proceedings of a Panel Discussion***

***Chair:*** **Carl E. Walter**
***Co-Chair:*** **Robert A. Krakowski**

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# Glossary

| | |
|---|---|
| ALMR | Advanced Liquid Metal Reactor |
| ANS | American Nuclear Society |
| bbl | barrel of oil = 42 gallons = 0.16 $m^3$ |
| BWR | boiling water reactor |
| CANDU | Canadian Deuterium Uranium |
| CTBT | Comprehensive Test Ban Treaty |
| DOE | Department of Energy |
| DPRK | Democratic Peoples Republic of Korea |
| EJ | exajoule = $10^{18}$ joule = 31.7 GWy |
| EPRI | Electric Power Research Institute |
| FMCT | Fissile Material Cutoff Treaty |
| FY | Fiscal Year |
| GDP | Gross Domestic Product |
| GHG | greenhouse gas |
| GWe | gigawatt electric |
| GWP | Gross World Product |
| HEU | Highly Enriched Uranium |
| HLW | High-Level Waste |
| HWR | Heavy Water Reactor |
| IAEA | International Atomic Energy Agency |
| IIASA | International Institute for Applied Systems Analysis |
| IMRSS | Internationally Monitored Retrievable Storage System |
| INFCE | International Nuclear Fuel Cycle Evaluation |
| IPCC | Intergovernmental Panel on Climate Change |
| kWh | kilowatt hour |
| LEU | Low-Enriched Uranium |
| LWR | Light Water Reactor |
| MC&A | Materials Control and Accounting |
| MHR-GT | Modular Helium Reactor-Gas Turbine (formerly High Temperature Gas-Cooled Reactor) |
| MOX | Mixed Oxide |
| MRS | Monitored Retrievable Storage |
| NAS | National Academy of Sciences |
| NPT | Non-Proliferation Treaty |

| | |
|---|---|
| OECD | Organization for Economic Cooperation and Development |
| OPEC | Organization of Petroleum Exporting Countries |
| PCAST | President's Committee of Advisors on Science and Technology |
| PgC | petagram carbon = $10^{12}$ kg C |
| ppm | parts per million |
| PRISM | Power Reactor, Inherently Safe, Modular |
| PUREX | Plutonium and Uranium Recovery by Extraction |
| PURPA | Public Utilities Regulatory Policy Act |
| PV | photo voltaic |
| R&D | Research and Development |
| TgC | teragram carbon |
| TRU | Trans-Uranic |
| TWy | terawatt–year = $10^{12}$ watt-year |
| U.S. | United States |
| UK | United Kingdom |
| UN | United Nations |
| WEC | World Energy Council |

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## THEME for the Panel Session

### NUCLEAR TECHNOLOGY—Global Accomplishments and Opportunities

### Scope

The panel reviewed the complete nuclear fuel cycle in the context of alternate energy resources, energy need projections, effects on the environment, susceptibility of nuclear materials to theft, diversion, and weapon proliferation. We also looked at ethical considerations of energy use, as well as waste, and its effects. The scope of the review extended to the end of the next century with due regard for world populations beyond that period. The intent was to take a long-range view and to project, not forecast, the future based on ethical rationales, and to avoid, as often happens, "long-range" discussions that quickly zoom in on only the next few decades. A specific nuclear fuel cycle technology that could satisfy these considerations was described and can be applied globally.

The panelists, with appropriate expertise, addressed these specific subject areas:

| | |
|---|---|
| Fossil Resources | Peter W. Beck, *Royal Institute of International Affairs* |
| Renewable Sources | Helena L. Chum, *National Renewable Energy Laboratory* |
| Effect on Environment | Steven Fetter, *University of Maryland* |
| Weapon Proliferation | William G. Sutcliffe, *Lawrence Livermore National Laboratory* |
| Fast Reactor Fuel Cycle | Marion L. Thompson, *Consultant* |
| Waste / Spent-Fuel | K. K. S. (Sam) Pillay, *Los Alamos National Laboratory* |

# Opening Remarks

## Carl E. Walter

When Ken Ferguson asked me at last year's ANS Winter Meeting in Washington to organize a panel session for this meeting, I came up with the topic **The Enduring Nuclear Fuel Cycle.** This topic had been very much on my mind since I became convinced early in 1993 that once-through, or even thrice-through fuel cycles (the highest extent of recycling that appears to be practical in light-water reactors), were so far from achieving the potential of nuclear power that something better had to be done. This is not to denigrate the other types of nuclear reactors that are being used successfully today and which certainly have a large number of advantages over fossil-fuel-fired power plants.

That 'something better' in my opinion is the advanced fast reactor with onsite fuel recycling. This type of a reactor system is two orders of magnitude more conservative of natural resources than other systems. At the same time, with appropriate design, operation, and management the fast reactor system is safe, economical, environmentally benign, and does not represent an unacceptable risk of enabling the construction of atomic bombs.

In selecting the members of this panel, I attempted to choose experts who were objective and who would bring diverse viewpoints to the discussion. I believe that I succeeded in meeting this objective. We will introduce the panel members later. At this time I want to thank Bob Krakowski for agreeing to chair this session with me. He has been of great help already.

In choosing the subjects to be discussed in the session, I have tried to ensure that all the facets of the nuclear fuel cycle are covered. The complete fuel cycle must be considered, it seems to me, in order to form an opinion of its merits. In the past, many discussions of the fuel cycle have neglected to do this. The complete fuel cycle has to be evaluated on the basis of its effects on the environment, alternative approaches, national security, and the standard of living of people today and in future societies.

Recently, I had the opportunity to visit several large cities on China's east coast. While my wife was in a gift store in one of these cities, I wandered outside the building and helped myself to a small piece of coal from a nearby pile. I saw many piles of coal at all the places that I visited. I'd pass this sample around, but it is too dirty, I mean really dirty. I also saw the dark smoke clouds that these piles of coal produced—graying the entire sky. On a clear day about an hour or two before sunset or after sunrise, we could look directly at the sun, a large orange disk. I have seen much brighter full moons! I understand that one can already detect Chinese smog in Hawaii.

I believe that this piece of coal is a significant symbol to remind us of what we must do to help China and the rest of the world including the United States avoid its use as much as possible. Let us demonstrate to them and the rest of the world how an Enduring Nuclear Fuel Cycle can improve the well being of all people.

Now, let us hear the presentations.

# Nuclear Energy in Context of World Long-Term Energy

P. W. Beck

## Introduction

The purpose set for this paper is to consider nuclear energy in the light of energy demand during the next century and the availability and economics of fossil fuels. Such a task would be sufficiently daunting when looking twenty years ahead; considering the future fifty to one hundred years hence is well-nigh impossible, especially as longer term technological advances and political developments are impossible to forecast so far ahead. Such an exercise, therefore, tends to concentrate on factors we believe we know or can forecast and ignore those, such as politics, too difficult to deal with. Past experience, however, should have taught us that most of our effort in forecasting, even for fields we thought we knew well, turned out quite different than what we envisaged. The only certainty about the longer term future is that it is unknowable.

Why then attempt the exercise? Although one cannot forecast, it is possible to achieve an understanding of the forces—political, technological, economic, etc.—that will affect the future of energy and such understanding can be of value in a strategic assessment of long-term aims and of short-term decisions to achieve these aims. As will be shown in this paper, that is the position in this case. Unless there is a connection between long-term studies and action needed in the short term, the purpose of such work is no more than to satisfy intellectual curiosity (or to achieve a doctorate).

The study is described in three sections. One section concentrates on future demand, another on supply, which includes comments about the relationship between the cost and price of oil, and the third on political factors and the effect these can have on the future of nuclear energy. A final section provides the conclusions.

## The Demand for Energy

The future demand for energy will depend on a vast number of assumptions about the future, from population growth, the scale and type of economic growth, to technological and political developments. Accepting that forecasting can have no reliability in such a case, a number of scenarios, making widely different assumptions, but still believed to be in the range of feasibility, have been drawn up by WEC/IIASA.[1]

Three families of scenarios were developed:

A. High economic and technological growth; characterized by large increases of wealth with technology unlocking more fossil resources and making more non-fossil sources available.
B. A medium case; this can be seen as a “business as usual” scenario, an extrapolation of present trends. From today’s perspective it could be seen as the most likely case, except that experience has taught us to be wary of trusting long-term extrapolations.
C. Policy driven in the direction towards sustainability; this assumes policy measures to accelerate improvements in energy efficiency and the development of sustainable energy resources.

Three variants were investigated for A and two for C which largely differ about assumptions regarding availability of fuels and technical progress in the development of energy resources. They are therefore more relevant to the energy supply picture and will be discussed in the next section. Some of the more important data from the scenarios are shown in Table 1.

The scenarios are not alternative predictions, but each explores the effect of alternative ways the future may unfold. The scenarios chosen are, of course, just three out of an infinite number of paths into the future and they were chosen to illuminate the wide range of possibilities. The many underlying assumptions are based on the judgments of the scenario writers and it could well be that strong adherents of one course or another could take issue with the data used; as an example, the assumption about energy savings might be seen as too low by conservation enthusiasts and quite unachievable by others. Although the ranges of assumptions are wide, they may not be wide enough for some tastes. Nevertheless, they seem wide enough to provide a testing challenge to possible strategies.

**Table 1. The WEC/IIASA scenarios**

| Scenarios | | A. High Growth | | B. Middle Course | | C. Ecologically Driven | |
|---|---|---|---|---|---|---|---|
| Energy Intensity Improvements | | medium | | low | | high | |
| Fossil Fuel Resource | | high | | medium | | low | |
| Other | | high | | medium | | high | |
| Environmental Taxes | | No | | No | | Yes | |
| **Year** | **1990** | **2050** | **2100** | **2050** | **2100** | **2050** | **2100** |
| Population × $10^9$ | 5.3 | 10.1 | 11.7 | | | | |
| Primary Energy, TWy | 12.9 | 35 | 63 | 28 | 49 | 20 | 29 |
| % in OECD | 47 | 27 | 18 | 28 | 16 | 21 | 11 |

The economic growth assumed is roughly similar for B and C, but rather higher for A. All the scenarios show a substantial increase in the demand for energy over the 1990 demand, but the level of increase to 2100 varies from a factor of five in Scenario A to just over two for Scenario C. One important assumption for all the scenarios is the vast increase in population, nearly all assumed to be within the developing countries. That, and the assumption of improved living standards in these countries, is the reason for the result that, as we go into the next century, the present developing countries are likely to become far larger energy users than the present OECD countries.

## Energy Supply

The situation on the supply side is perhaps even more uncertain. An assessment should look at the resource base of the many alternatives, their relative economics, take into account regional, political, and policy constraints and advantages including those set by environmental issues, and derive from such data a possible balance between the various energy sources. The WEC/IIASA scenarios have attempted to do this and they, therefore, contain estimates of how the various energy sources might balance the demand. The exercise required a vast number of assumptions and the major ones, which are discussed in the publication, appear again to have been chosen to provide a wide range of answers for the various scenarios. For good reasons discussed later in this section, the scenarios do not consider the relative economics of the various energies, but make the general assumption that the balances assumed in a specific year will be found to be economically justified under the circumstances valid at that time.

The assumed resource base of fossil fuels for the scenarios is shown in Table 2. It also shows comparable figures for uranium. The definitions used in the table are as follows:

- **Reserves** are taken to be those quantities that can be recovered, with reasonable certainty based on geological and engineering information, from known reservoirs using known technology under existing economic conditions.
- **Resources** have less certain geological assurance or cannot be as yet extracted with present technological means under existing economic conditions.
- **The resource base** is the sum of the two. As technology advances, reserves will increase at the expense of resources and this has been happening since the dawn of the oil industry. The figure for reserves is thus a very misleading measure of future availability of fossil fuel and, indeed, of uranium also.
- **Novel type of resources** cover very speculative plays; methane hydrates or uranium from seawater are examples. They are possible sources for the future, but are not taken into account in the scenarios.

Within the three scenarios, three variants were looked at in Scenario A and two in C; no variants were developed for B.

- **A1** is technologically very challenging, especially in the field of oil and gas, so making it possible to make good use of the resources in the first half of the century. By the second half, fossil fuels are beginning to be phased out with renewables and nuclear taking the strain.
- **A2** concentrates on far greater use of coal than in A1 and does, therefore, depend on less concern about $CO_2$ emissions.
- **A3** is driven by technological advances in nuclear and renewables which make it possible to phase out coal and oil by the end of the century.
- **B** assumes a continuation of today's trends with fossil fuels still taking over 50% of demand by the end of the century.
- **C1** assumes that nuclear energy will be phased out by the end of the century.
- **C2** presumes that it will be possible to develop nuclear processes which are easily adapted to the developing countries and are socially acceptable in general.

**Table 2. Estimates of energy resources, TWy**

| | 1990 Consumption | Reserves (1) | Resources (2) | Resource base (1+2) | Novel type resources |
|---|---|---|---|---|---|
| Oil | 4.5 | 480 | 670 | 1150 | 2600 |
| Natural Gas | 2.4 | 470 | 750 | 1220 | 400 |
| Methane Hydrates | | | | | 26000 |
| Coal | 3.1 | 850 | 3900 | 4750 | 4200 |
| Total | 10.0 | 1800 | 5320 | 7120 | 33200 |
| Uranium[(a)] | 0.7 | 80 | 280 | 360 | 200 |
| with recycle[(b)] | | 4800 | 17000 | 21800 | 12000 |

(a) using thermal reactors only (b) including use of fast reactors

Table 3 provides a breakdown of the energy mix for these scenarios for the year 2050. It will be seen that the proportion of nuclear fluctuates widely between scenarios and the text stresses that the expansion to achieve the higher numbers requires the assumption that the energy form will have made technical advances so as to become generally acceptable. Table 4 shows the required nuclear capacity for the scenarios from which it can be seen that, say for 2050, the minimum is roughly today's capacity, and the maximum is some five times larger. For 2100, capacity could be up to 20 times larger.

As regards renewables, (which here include non-commercial energy, presently perhaps around 10% of total energy use, but likely to fall below 5% as future total energy demand increases), the highest figure for 2050 is just under 40%. Other organizations, not all connected to the environmental lobby (e.g., BP and Shell), have gone on record that by that time and given favorable conditions, up to 50% could be met by renewables.

The general picture arising from the WEC / IIASA scenarios is that there are adequate fossil fuel resources to take much of the strain of increasing energy demand for a number of decades. However, beyond mid-century this may become more difficult and could require the development of unconventional and possibly high-cost resources.

But what is high cost and what effect could such higher costs have on price? There are indications[3] that most of today's oil has a production cost of below $7 / bbl and that the cost of unconventional sources could be in the region of $20 to 25 / bbl. Conventional wisdom could, therefore, assume that oil prices are likely to rise substantially so as to make investment in such development worthwhile. There are, however, two reasons why such an increase may not happen.

**Table 3. Energy mix under various scenarios for the year 2050**

| Scenario | | 1990 | A | | | B | C | |
|---|---|---|---|---|---|---|---|---|
| | | | A1 | A2 | A3 | | C1 | C2 |
| Primary Energy, TWy | | 12.9 | 35 | 35 | 35 | 28 | 20 | 20 |
| Mix, %: | Coal | 23 | 15 | 32 | 9 | 21 | 11 | 10 |
| | Oil | 36 | 32 | 19 | 18 | 20 | 19 | 18 |
| | Natural Gas | 18 | 19 | 22 | 32 | 23 | 27 | 24 |
| | Nuclear | 5 | 12 | 4 | 11 | 14 | 4 | 12 |
| | Renewables* | 18 | 22 | 23 | 30 | 22 | 39 | 36 |

* Includes non-commercial and hydro

**Table 4. Nuclear capacity under various scenarios, GWe[2]**

| | Scenarios | | | | | |
|---|---|---|---|---|---|---|
| Year | A1 | A2 | A3 | B | C1 | C2 |
| 2020 | 646 | 417 | 732 | 645 | 480 | 605 |
| 2050 | 1875 | 782 | 1860 | 1915 | 380 | 1240 |
| 2100 | 3680 | 6415 | 6725 | 5700 | 0 | 2750 |

1990 capacity: 357 GWe

First, the assumption that the price of oil tends to follow its cost of production has not happened in the oil industry for the last 150 years. Except for short periods, when prices dropped to very low values, prices have usually had a major political component, first through cartels, until these were outlawed, and over the recent period, by swing producers within OPEC, especially Saudi Arabia. At least until recently, these latter have considered it worthwhile to shut in their own (very cheap) production to stabilize the price at levels of $18–22/bbl. They thus maximize their return per barrel, rather than on total volume. With the average production cost in non-OPEC countries probably below $10/bbl, the margin between cost and price could be creamed off by taxation, while still leaving sufficient incentive for oil companies to continue exploration and investment.

Under such a system the effect of increased production cost in non-OPEC countries is a matter of politics rather than strict economics; countries could cut taxes to keep oil activity at the wished-for level, or they could keep taxes steady and see a reduction in oil activity. Of course, such a system may not survive into the long term, but for now at least, it is difficult to envisage a world pricing system which can tie short-term price movements to the long-term supply/demand and cost situation. Even so, with today's costs so much lower than price, even a three-fold increase in cost may, if governments so wish, only require a 50% increase in price.

The second reason, namely the effect on cost of technological change and experience, makes the assumption of a major rise of oil prices even more hazardous. During the late 1970s it was expected that oil prices would rise substantially and many oil development projects were based on that presumption. When prices proceeded to fall instead, such projects, as well as much of the exploration strategy had to be reviewed—with startling results. Proving the saying "To be hung tomorrow concentrates the mind wonderfully," innovative thinking made it possible to reduce the development costs of some offshore fields in the UK by as much as 50%[4] and use of three- (now even four-) dimensional seismic surveying vastly improved the efficiency of finding and delineating new oil and gas fields. Similarly, the cost/unit of Liquid Natural Gas (LNG) plants seem to have been reduced by nearly 40% over the last twenty years.[5] As there are yet numbers of new ways of saving costs, it is as of today, quite impossible to tell whether the costs of unconventional oil and gas will really be as high as now assumed.

Pressures on costs have been successful in many other energy fields and especially in the renewable areas, such as windmills and solar cells. Presumably due to recent low orderings and the strict regulatory requirements, only nuclear energy can't show such a trend.

The two reasons—uncertain relationship between price and cost and no indication how far future costs will be affected by experience and new technology—make longer-term relative cost calculations of competitive energy sources pointless and perhaps dangerous. There are, therefore, good reasons why no such calculations were included in the WEC/IIASA scenario publication.

Lastly, it should be noted that there are a few strongly dissenting voices around, who believe that oil production will start declining far earlier, than either assumed in the scenarios or by the oil industry and its academic or financial analysts. Such opinions believe that this could already happen within the next decade, that it will trigger an oil price shock and have a considerable political effect on the energy scene of the next century.[6] Although there are only a few such voices, it has to be said that in the past, maverick dissenters often proved to be right.

## The Political Dimension

The scenarios make one strong assumption, namely that there will be no major discontinuity. They could hardly do otherwise, but in real life a period of fifty to a hundred years without such a discontinuity cannot be imagined. The future is uncertain and in strategic terms, the answer to uncertainty is flexibility, but flexibility can be expensive and this is where politics comes in. The politics of energy is a vast subject and only three aspects, which are seen to be important for this paper, will be discussed:

- The *change of mood* about energy by governments over the last twenty years.
- *Public opinion* about nuclear energy.
- The debate about global warming and the *search for sustainability*.

## Change of Mood

Much of present nuclear capacity was planned in an era when energy security was in the forefront of political debate. Now, with a surplus of energy, the worry about energy security has vanished and the experience during the Gulf War left the impression that the world can now deal with disruptions.

At the time, power generation was seen as a natural monopoly either operated by the state or under strict regulatory control. Today's thinking is quite different; concerns seem more about efficiency brought about by competition, with reduction of state control being considered in many countries. New technology has made it possible to provide competitive supply to individual businesses and households and there is expectation that under such circumstances competitive pressures can make price regulation unnecessary. Only time will tell whether this is really so.

Continuation of this trend implies that governments would leave decisions about new power capacity to the market and this may well have a considerable effect on the attractiveness of nuclear power, especially vis-à-vis combined cycle gas burning stations. Such stations have the advantage of lower capital cost per unit of output, can be built in smaller units, have perhaps half the building time and far greater acceptance by the public, making finding suitable sites much simpler. Furthermore, if there is real competition, companies would be justified to require a normal commercial return, rather than a lower utility return, as at present. That makes the choice of gas-fueled plants with lower capital cost and shorter building time even more attractive.

As long as natural gas or oil can be purchased at a competitive price, the choice for commercial companies operating in a free market is, therefore, simple—they are unlikely to choose nuclear power when considering new capacity unless their governments pressure them, possibly through the tax system, to do so. Only when it becomes reasonably certain that fossil fuel prices will increase substantially and stay at the higher level, would it be sensible for a company to choose nuclear power voluntarily. In the light of the previous section, there may be a long wait before this might happen.

Over the next twenty years, many of the present nuclear units will come to the end of their design lives. If governments leave the replacement decisions to the market, it may well be that only a few organizations will choose the nuclear option.

## Public Opinion

Whether justified or not, there is considerable public concern about nuclear energy. It is strong enough to affect policy in many democratic countries with political parties and even some international organizations careful not to be seen as supporting this energy form. Because the industry strongly disagrees with the public's perception, it has, so far, concentrated on public relations to change this perception. It also appears to believe that sooner or later the benefits of nuclear power in reducing $CO_2$ emission and in reducing the demand for fossil fuel will change the public mood. So far, however, there are no indications that such a stance will do the trick. Instead, the industry will have to deal with the many perceived problems. Other energy forms have made use of improved technology to reduce costs and have become more dynamic. Few members of the public will see the nuclear industry in this way. It is seen as dangerous, proliferation prone, expensive, secretive, and with no acceptable answers to the disposal of its long-lived waste. It is accused of being stuck in a 50-year time warp and it itself appears to see virtue in being "mature."

To become more acceptable the industry will have to be seen making progress in at least the following four areas:

1. **Reactor designs that are safer** than today's designs, especially under conditions of mal-operation or lack of adequate maintenance.
2. **Improved nuclear power economics**, especially as regards the capital cost per power produced, and made more applicable to the developing countries.
3. **Effective solutions for the secure and acceptable disposal of spent fuel.** If that includes reprocessing, means would also have to be found to ensure that such activity will not increase the risk of nuclear weapon proliferation. Methods, which are acceptable to the public, for storing or transmuting long-lived radioactive waste and plutonium containing materials would also have to be developed.
4. **Public assurance** that *internationally accepted* systems for setting standards and monitoring will be in place to ensure nuclear safety everywhere.

Technological developments during the last decade have shown ways of possibly meeting the first three conditions but so far only in laboratories. Far more work would have to done before these could be ready for commercial application. Achieving this would demand a considerable effort culminating with testing on a commercial scale that might take 20–30 years and cost possibly $ 10–20 billion. Although such a delay may be acceptable and provide time to tackle the fourth point, there must be grave doubts whether, under present circumstances, funds for such a program will be forthcoming. Opinions, however, can change and if, say, during the next energy crisis (which is bound to come sooner or later), the industry has well-developed plans to tackle its problems through a world-wide research and development program, it may be able to attract support.

Decisions in this area are not helped by the fact that the industry is split about the way forward. Some argue that today's proven technology meets all the criteria and is best placed to achieve major expansion, whilst others believe that different fuel cycles may stand a better chance of finding public acceptance. There are also differences about the use of fuel recycling. Unless such differences are resolved so that the world-wide industry can speak with a clear and convincing voice, the *possibilities for making nuclear power more acceptable* are not good.

## Search for Sustainability

Were nuclear energy more acceptable, it would be seen as an obvious choice for expansion if there is pressure to reduce $CO_2$ emission. However, such a choice would imply that by the end of the century the proportion of primary energy from this source could be well over 20%, compared to some 6% today. The industry could then be between ten and twenty times larger than now. (See Table 4.) Would there be enough uranium and possibly thorium? According to present estimates of reserves, perhaps not, but bearing in mind how reserves expand when there is a real effort to find more, it is quite likely that there would be adequate raw-material even without the use of recycling.

The world is, however, also looking for sustainable energy sources. Without fast reactors and fuel recycling, nuclear energy may only be in the same league as fossil fuels. With fast reactors and fuel recycling, resources may last millennia which surely would put nuclear into the 'sustainable' category. As there may not be any need for fast reactors (or other means of making better use of uranium) until mid-next century, there should be no need to rush their development.

## Conclusions

Using the WEC / IIASA scenario as a basis, this paper comes to the following conclusions:

- There is the likelihood of adequate resources of fossil fuel for a number of decades, though there may be problems by the second half of next century, especially if action on global warming will have to be taken.
- Nuclear energy could become an important source of energy by the second half of the next century, but if it does, it would have to have the ability to take on a major role, say 20+% of total primary energy.
- There are doubts whether present technology, now half a century old, is adequate for such a large-scale role, especially in view of the adverse public perception of today's technology. This point is made strongly in the scenario publication[1] and by others.[7]
- Perhaps the key conclusion is that the industry has to make a major effort to make itself more acceptable to the public. Without such an achievement it will be difficult to convince anyone, and especially governments, that in view of the vast uncertainties ahead, it must be prudent to keep the nuclear option open. Should conditions be right, the industry should be ready to expand rapidly later in the century.

Of course, it is well known that the industry has been working hard to achieve the good reputation it believes it deserves, but, so far it has not been successful. A recent paper by a social scientist included a guide ( suggested with 'tongue slightly in cheek') about how to turn even a minor environmental risk into a public relations disaster.[8] The five essential steps can be paraphrased as follows:

1. The "Expert" knows best. To question him / her already shows ignorance.
2. Be wise only after the event. Never anticipate the worst, always hope for the best.
3. Blame someone who is powerless to fight back.
4. Only manage what you can measure. Quantitative risk assessment made as complex and opaque as possible can be a potent weapon.
5. What is done is done; anything else is too expensive. In any case, many risks are unknowable and therefore unmanageable.

To an outsider like the writer, it seems that the industry has made use of most of these steps and its failure, so far, is therefore hardly surprising. An alternative strategy is needed which accepts that perceptions, whether correct or not, have to be treated seriously; they are seen as real by the opposition and can therefore have real consequences.

Perhaps a dialogue with the opposition (or to start, with the more moderate members) could be a beginning. Its aim could be,

- *Firstly*, to reach a better understanding of each others' position.
- *Secondly*, to see whether agreement could be reached that, with all the uncertainties ahead, it is important to keep the nuclear option open.
- *Thirdly*, to consider what an acceptable nuclear industry might consist of and how one could develop the necessary technology to make it possible.

Because of the necessity to meet strict safety and security regulation and the need for commercially sized demonstration units before a new process can be accepted by the industry, the development of new or radically changed processes takes, possibly, twenty to thirty years.

As indicated earlier, cost are likely to be high, but expenditure would be spread over many years. If the industry could achieve international agreement of co-operation for such developments, rather along the lines achieved in the field of high-energy physics, the burden on individual companies and / or countries may well be bearable.

The approach of achieving a fruitful dialogue may well fail, but it is surely worth trying, rather than continue the present process of sniping at each other.

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# Two Decades of Progress in Research, Development, and Commercialization of Renewable Energy

Helena L. Chum

## Renewable Energy Today

Renewable energy today contributes as much to the energy mix consumed in the U.S. as nuclear power. In 1995, 6.8 EJ (220 GWy) primary nuclear energy and 6.4 EJ (200 GWy) of renewable energy technologies were used. Among the renewable energy technologies, hydroelectric contributed 50.6%, biomass 43% (as electricity, residential and commercial heat, industrial process energy, and transportation fuels), geothermal 4.8%, solar 1.1% (as thermal and photovoltaic (PV) applications), and wind 0.5%. Together, nuclear and renewable energy represent 15.5% of the total energy mix consumed in the U.S., which was 85.8 EJ (2.87 TWy) in 1995.[1]

The installed capacity of grid-connected renewable energy technologies is 94 GW or 12.2% of the total U.S. electric generating capacity. While capacity is important, because renewables include both base load and intermittent technologies, a more important factor is the total renewable electricity generation. In 1995 it is 47.4 GWy of which 80% is provided by hydro, 15.1% is supplied by biomass, 3.8% by geothermal, and 0.8% by wind, and 0.3% by solar.[1]

Excellent reviews of the past two decades of progress in renewable energy technologies are available both at the national and international levels.[2,3] In the U.S., the growth of implementation of renewable sources of energy was spurred by PURPA legislation enacted in 1978. It required payment of the avoided costs of incremental capacity installation to be given by utilities to qualified developers of non-utility generation and independent power production as determined by the Federal Energy Regulatory Commission. In fact, with this incentive, an investment of $15 billion established 66,000 jobs in the biomass industry alone that netted about $1.8 billion / y. The Geysers' geothermal complex was further developed as a result of PURPA. Embryonic wind industries continued their development and installation of wind farms, primarily in California. Some of the renewable production will be phased out as these advantageous contracts end but others will continue as their capital investment has been amortized.

Renewable energy resources generally are not subject to depletion. Heat and light from the sun, the force of the winds, organic matter (biomass) grown in short cycles, falling water, and ocean energy are inexhaustible sources. Geothermal heat from inside the earth is another source depletable over very long periods of time. Worldwide, 1,000 times more energy reaches the surface of the earth from the sun than is released today by all the fossil fuels consumed.[3]

Though the large stores of primary energy exploited are often scattered, they can be converted in various ways into usable forms of energy—heat, electricity, and fuels—by a wide array of technologies under development and some already commercialized. We will focus on electricity production routes.

As shown in Figure 1, solar, wind, biomass, and geothermal resources in the U.S. are not uniformly distributed. They complement each other, and taken together, can contribute appreciably to energy security and regional development. At the same time, these technologies offer substantial environmental benefits over conventional resources principally when

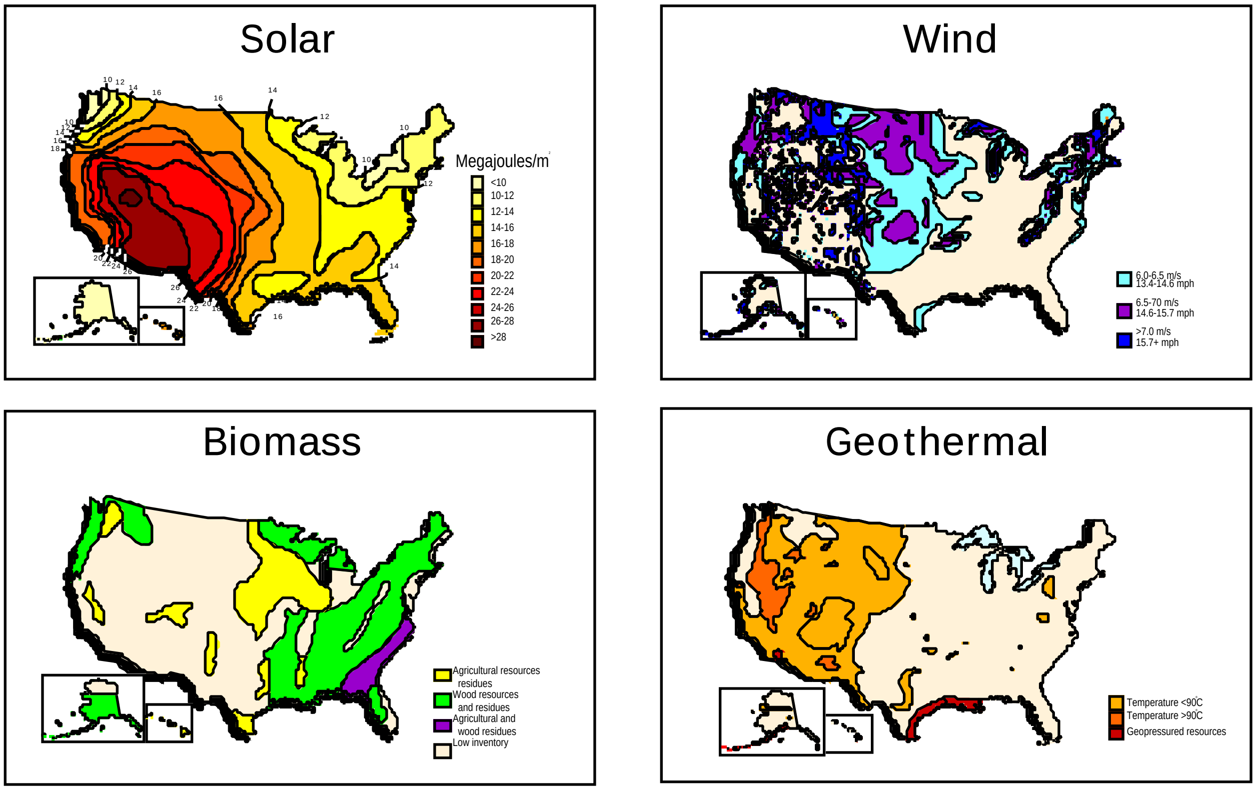


**Figure 1. U.S. renewable energy resources**

considered on a life-cycle basis. The details on over 7,000 facilities that generate U.S. grid-connected electricity from renewable resources is available electronically.[4]

Most renewable energy systems are modular, allowing flexibility in matching load growth. They span specialized energy niche markets, decentralized, and centralized energy applications. Centralized scale applications are relatively capital intensive (compared against competing conventional technologies like natural gas combined cycle) and require significant investments in capturing the disperse resource. However, after the investments have been made, the economics of renewable energy technologies improve in comparison with conventional technologies since operating and maintenance costs are low compared with using conventional fuels, particularly as fuel prices increase in the future. The progress in improvements in the cost effectiveness of renewable energy technologies is shown in Figure 2.

## Photovoltaic Energy[1-6]

Photovoltaic power generation involves the direct conversion of sunlight into electricity using solid state devices, the PV cells. Various materials can be used in thin layers—silicon and a variety of sulfides, selenides, and other derivatives of appropriate metals such as cadmium, indium, etc. Arrays of cells make panels that reliably produce electricity with no moving parts and no emissions in operation.

R&D continues for the development of highly efficient semiconductor materials, while manufacturing research is decreasing the cost of polycrystalline and amorphous silicon cells being commercialized by a variety of companies worldwide. Progress in the area has been significant as a result of a DOE program,[5] in partnership with the private sector and academia, and other government programs.[6]

In 20 years of R&D by industry, laboratories, and academia, a factor of 10 decrease in cost of PV electricity has been achieved. The cost of electricity went from $0.90 / kWh in 1980 to around $0.20 / kWh in the 1990s. Capital costs of systems decreased by a factor of 4–5. For instance, capital cost in the 1980s was $20 / W and was reduced to under $8 / W in the 1990s and continues to go down as manufacturing experience and production volume increase.[7] The reliability of the systems increased although storage can still be a problem for standalone systems. These improvements enabled the commercial penetration in certain applications.

In 1987, the industry produced laboratory scale silicon cells in small sizes (~1 $cm^2$) at 15% conversion efficiency. Two years later, the industry was able to make hundreds of cells with 100 times that area at 11% efficiency. Improvements in processing in the 1990s now produce cells at 2–3 times the areas of the early 1990s at higher efficiency of conversion.[7] Some progress results from government programs such as PVUSA (PV for Utility Scale Applications) and PVMat (PV Manufacturing Technology).[8]

Today, commercial PV applications include space power, communications, and consumer applications such as calculators and watches. Markets such as remote industrial, rural off-grid electrification, peaking electricity, and bulk power production have increased volume but require decreases in the cost of electricity. The market size for electricity is price elastic. As the PV system price is reduced from $7 / W to $3.50 / W, the market is projected to grow from $800 million to $10 billion / y. With another factor of ten reduction in system price, the market size is estimated at $100 billion. With this sizable economic potential the commercial attention the field is receiving is understandable.

Since 1988, PV powers 150,000 homes in the U.S. and 8 million homes in the developing countries, where an estimated 2 billion people live without the comforts electricity provides.

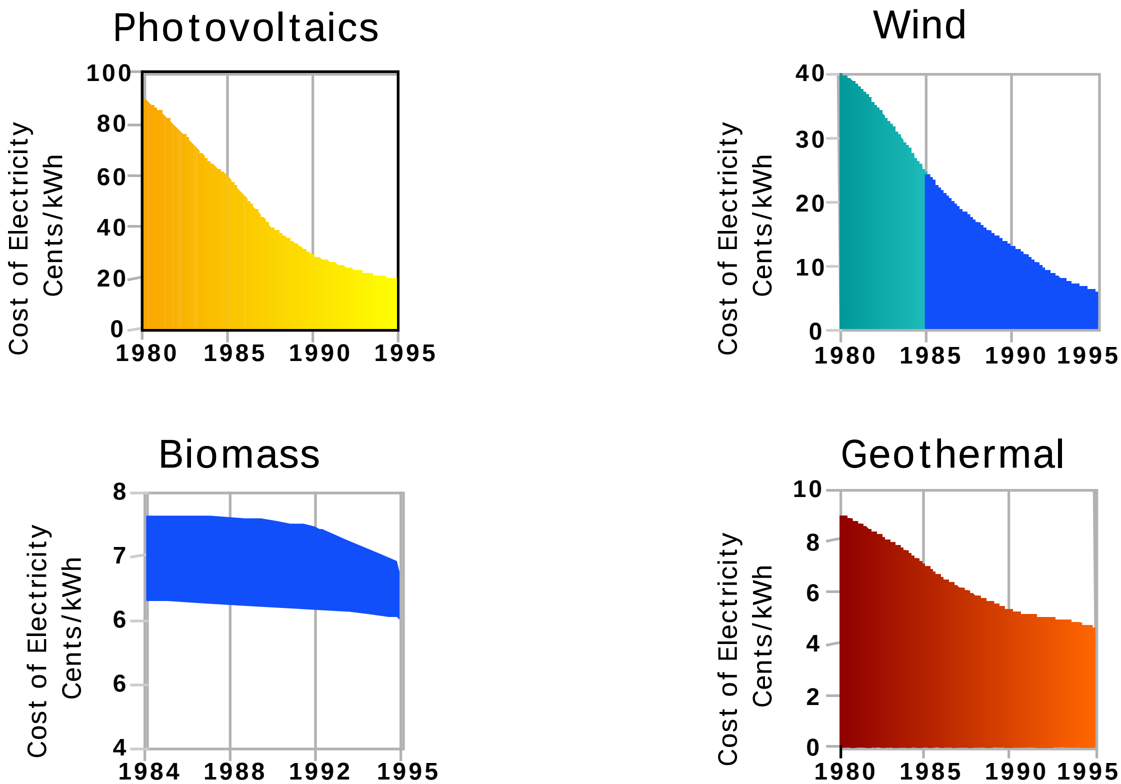


**Figure 2. Cost of electricity from select renewable energy technologies**

These initial installations allowed developers to establish better designs, to investigate a variety of applications, and to obtain feedback from a variety of users.

Incorporation of PV in building materials is a growing area. Some examples of actual PV systems in operation are illustrative. Systems installed in 1982, for instance, at the Solarex facility in Frederick, MD, deliver an annual average of 33.3 kW (14.4 W / $m^2$) from 2320 $m^2$. The Tuckahoe library in New York delivers, on average, 3.1 kW (17.3 W / $m^2$) from a 178-$m^2$ system. A 50-$m^2$ PV roof system in Atlanta, GA delivers nearly an average of 150 W (3.0 W / $m^2$) from amorphous silicon shingles. A complete guide on resource, system design, installation, and commissioning as well as the technologies for photovoltaics, electronics, and storage is available.[9]

While some forms of these technologies are mature for specific localities today, improvements in technologies and systems will open up larger markets for more widespread applications in the future. Another measure of the progress in this field is the number of manufacturing companies created. Today, more than 31 module manufacturers and 86 systems designers and installers provide specific equipment. In addition, 44 companies provide the balance of the system that includes the storage batteries. More than 61 companies manufacture related products. There are dozens of organizations providing equipment testing and standards. More than 25 consulting companies are active in the field. In 1997, U.S. shipped 53 MW out of 127 MW worldwide. Japan and Europe shipped 35 and 29 MW, respectively.[10]

Finally, multinational companies are now very active in the business of photovoltaic energy. This is a good indication of the increasing maturity of the technologies and of the market potential leading to serious commercialization intent. Both Royal Dutch Shell and British Petroleum created companies for this purpose that operate in several countries. For instance, Shell Solar has a PV manufacturing facility at Helmond, Netherlands currently expanding from 5 to 20 MW. They manufacture 50 W kits for homes in developing countries.[11] BP Solar Australia has won the contract to supply the first 500 solar power systems for the athletes' village in the recently established Sydney suburb of Newington, adjacent to the Olympic site at Homebush. In total, 650 1-kW units will be installed, feeding the excess electricity generated into the Sydney electricity grid.[12] In the U.S., Amoco / Enron Solar is the largest U.S.-owned manufacturer and marketer of solar PV modules and the second largest worldwide.[13]

## Wind Energy[1,2, 14,15]

Wind power systems convert the kinetic energy of the wind into other forms of energy such as electricity. There are two basic configurations: vertical and horizontal axis turbines. Both types comprise a rotor with one or more blades, a drive train including a gearbox and generator, a tower to support the rotor, and several subsystem controls. The amount of energy that a turbine can extract from wind is related to the wind speed. Below about 4 m / s, the wind is not strong enough to overcome the resistance of the blades. The power output increases rapidly with the wind speed between 4–12 m / s.

R&D led to significant reductions in the cost of wind energy. In the 1980s the cost of electricity was $0.38 / kWh. Today, in several places wind can produce electricity ten times less expensively. This number is competitive with other conventional resources in specific sites. The capital cost decreased from $2,200 / kW in the 1980s to less than $1,000 / kW in the 1990s, more than a factor of two.

In North Dakota, wind regimes are excellent and it is estimated that there is enough resource to supply 36% of the electricity consumption in the lower 48 states. In England, there is a very good match between the resource and the loads generated by consumers during the year.

In fact, the European countries are now moving ahead faster than in the U.S. and in 1995 their installed capacity surpassed that of the U.S., steady at 1.6 GW. More than 20,000 grid-connected turbines are operational in the world with an estimated installed capacity of 5 GW at the end of 1996. These turbines deliver an annual average of about 0.8 GW. Several times that amount in small turbines deliver water when there is no rainfall in many countries. China alone has more than 100,000 small turbines.[2]

For 50-m-diameter turbines, with turbines spaced at 10 by 5 diameters in a wind farm located in a 7–7.5 m / s wind speed range (class 4), we can calculate the resource conversion (assuming 25% efficiency, 25% power losses). The wind power density is 450 W / $m^2$ (swept area) and thus the wind power intercepted by the turbines is 7.1 W / $m^2$ (land area). With this intercepted wind power, the electric power output is 1.33 W / $m^2$ which would produce annually 11.6 kWh / $m^2$. So, an area of 460,000 $km^2$ with class 4 wind (constant) could produce about 600 $GW_e$ or 5,300 TWh. This land area represents only about 6% of the U.S.[14]

Better understanding of wind farm siting can minimize the interactions of turbines with migratory birds. An avian literature database (http: / / www.nrel.gov / wind / avianlit.html) is available.

Wind energy is also enjoying the entry of large multinational companies in order to accelerate the commercial development of this field. Enron has recently purchased Zond, a small wind company in the U.S., and now is moving the commercialization of their turbines with Enron Wind Corp.[13] The worldwide potential is quite large for electricity and mechanical energy applications.

## Geothermal Energy[1, 2, 16]

Geothermal energy is heat stored in rocks and fluids inside the earth. Geothermal resources come in five forms: hydrothermal fluids, hot dry rock, geopressured brines, magma, and ambient ground heat. Of these five, only hydrothermal fluids have been developed commercially for power generation. Three technologies can be used to convert hydrothermal fluids to electricity. The type of conversion used depends on the state of the fluid (whether steam or water) and its temperature:

> **Steam**—Conventional steam turbines are used with hydrothermal fluids that are wholly or primarily steam. The steam is routed directly to the turbine, which drives an electric generator, eliminating the need for the boilers and fossil fuel of conventional power plants.
>
> **High-temperature water**—For hydrothermal fluids above 200 °C that are primarily water, flash steam technology is usually employed. In these systems, the fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or flash, to steam. The steam is used to drive a turbine, which again, drives a generator. Some liquid remains in the tank after the fluid is flashed to steam; if it's still hot enough, this remaining liquid can be flashed again in a second tank to extract even more energy for power generation.
>
> **Moderate-temperature waters**—For water with temperatures less than 200 °C, binary cycle technology is generally most cost effective. In these systems, the hot geothermal fluid vaporizes a secondary—or working—fluid, which then drives a turbine and generator.

Steam resources are the easiest to use, but they are rare. The only steam field in the U.S. that is commercially developed, The Geysers, is located in Northern California. The Geysers began producing electricity in 1960. It was the first source of geothermal power in the country and is now the largest single source of geothermal power in the world. The Geysers plant has an installed capacity of 2 GWe. Photographs of some Geysers stations are shown in Figure 3.[17]

Hot water plants, using high- or moderate-temperature geothermal fluids, are a relatively recent development. However, hot water resources are much more common than steam. Hot water plants are now the major source of geothermal power in both the U.S. and the world. In the U.S., hot water plants are operating in California, Hawaii, Nevada, and Utah.

## Biomass[1,2, 18-20]

Biomass includes plant materials-such as wood and its wastes, herbaceous and aquatic plants, agriculture crops and their residues, industrial and processing wastes, and the organic portion of municipal wastes. Biomass is the result of storing sunlight as chemical energy in plants. Through photosynthesis, sunlight transforms carbon dioxide from the atmosphere and water into complex plant polymers over short periods of time. Using biomass as renewable energy cycles carbon dioxide in and out of the atmosphere. Use of biomass as a material or durable product retains carbon dioxide, derived initially from the atmosphere, in the material.

By its diverse nature, biomass is the most complex renewable resource. It has a variety of uses including food, feed, fibers used by the pulp and paper industries, materials produced by the wood products industry, and energy. A rough estimate of the primary energy content of biomass for all uses, worldwide, in 1995 is 60 EJ or about 2 TWy. For comparison with this worldwide value of biomass energy content, in 1995 the actual use of biomass as primary energy in the U.S. was 0.1 TWy compared with the overall U.S. primary energy consumption of 3 TWy.

In the last two decades, biomass power has become the second largest renewable source of electricity after hydropower. Similar to hydropower and geothermal energy, biomass plants provide baseload power to utilities. Biomass power plants are fully dispatchable—they operate on demand whenever electricity is required. If biomass is cultivated and harvested properly, it is a renewable resource that can be used to generate electricity on demand, with no net contribution to global carbon dioxide. About 350 biomass (not municipal waste) power plants with a combined rated capacity of 7 GW feed electricity into the nation’s power lines, while another 650 enterprises generate electricity with biomass for their own use as cogenerators. The biomass power industry created by PURPA was based primarily on the use of biomass residues with condensed steam technologies that are about 20% efficient.

Advances in technology can double or nearly triple the efficiency of simple condensed steam. For instance, integrated gasification combined cycle can be coupled with higher

**Figure 3. Examples of power plants at The Geysers geothermal facility in California**

efficiency turbines or fuel cells for power generation. A review of the industry, its achievements, and current programs developed with many partners in industry, academia, and DOE in collaboration with the U.S. Department of Agriculture can be found in the literature.[20]

At present, several concepts of integrated gasification combined cycle are being developed worldwide. Examples of U.S. technology demonstration sites are the Batelle Columbus Laboratories indirect gasification concept being scaled up by FERCO at the McNeil Station (VT) and the Institute of Gas Technology's high pressure concept being scaled up by PICHTR and Westinghouse Electric in Paia, Maui HI [20] and elsewhere in the world by Carbona.

The Vermont project's detailed design and construction are completed for a 15 MW installation that will complement the existing 50 MW output of McNeil Station (the biomass-derived gas is cofired with the wood). Demonstration of this U.S. technology at a utility power station is intended to buy-down the perceived risk among domestic and international power project developers. It will also provide significant market opportunities for advanced-cycle, high-efficiency biomass power generation systems for application in domestic and international markets in the pulp and paper industry and in direct power generation. The schematic of the development in Burlington is shown in Figure 4.

At a biomass to electricity efficiency of 20%, it is necessary to collect biomass from a 5 $km^2$ area, assuming an annual biomass productivity of 1.13 dry $kg/m^2$. Increases in efficiency of conversion or of biomass productivity reduce this area requirement. Doubling the conversion efficiency at the same biomass productivity, as could be expected for an integrated gasification combined cycle system, could reduce the area requirements to 2.6 $km^2$. A 60% efficient conversion system, which could be achieved with fuel cells, would require only 1.7 $km^2$ with the same biomass productivity.

Given that quantities of residues and wastes are finite, for large-scale operations dedicated biomass feedstock production is contemplated either for specific energy production or for making multiple energy and non-energy products. Examples include short rotation woody and herbaceous species. Woody species include poplar, salix (willow), eucalyptus, etc. In the case of herbaceous species, native American grasses that dominated the prairies of this country in the past are considered such as switchgrass. Alternatively, forage grasses like alfalfa can have multiple uses—the leaves can yield a protein while the stems can be used for power generation.[20]

DOE aims to develop and demonstrate environmentally acceptable crops and cropping systems for producing large quantities of low-cost, high-quality biomass feedstocks.[21] DOE has screened more than 125 tree and non-woody species and selected a limited number of model species for development as energy crops. Several tools—databases and models—are available:[21]

- BIOBIB: a searchable bibliographic database of articles, reports, and conference papers authored by DOE staff, contractors, and cooperators
- ORECCL: a county-level database on energy crops, which encompasses all U.S. counties and provides easy access to energy crop information specific to state or county
- BIOCOST: an Excel-based model with a graphical interface that lets the user select a region and then specify values for several variables including expected yields, land rents, labor costs, and chemical, fertilizer, fuel, and planting stock prices.

A considerable effort in analyzing the entire life cycle for biomass energy was completed recently.[22] A life cycle analysis identifies, evaluates, and helps minimize the environmental impacts of a process. Material and energy balances quantify the emissions,

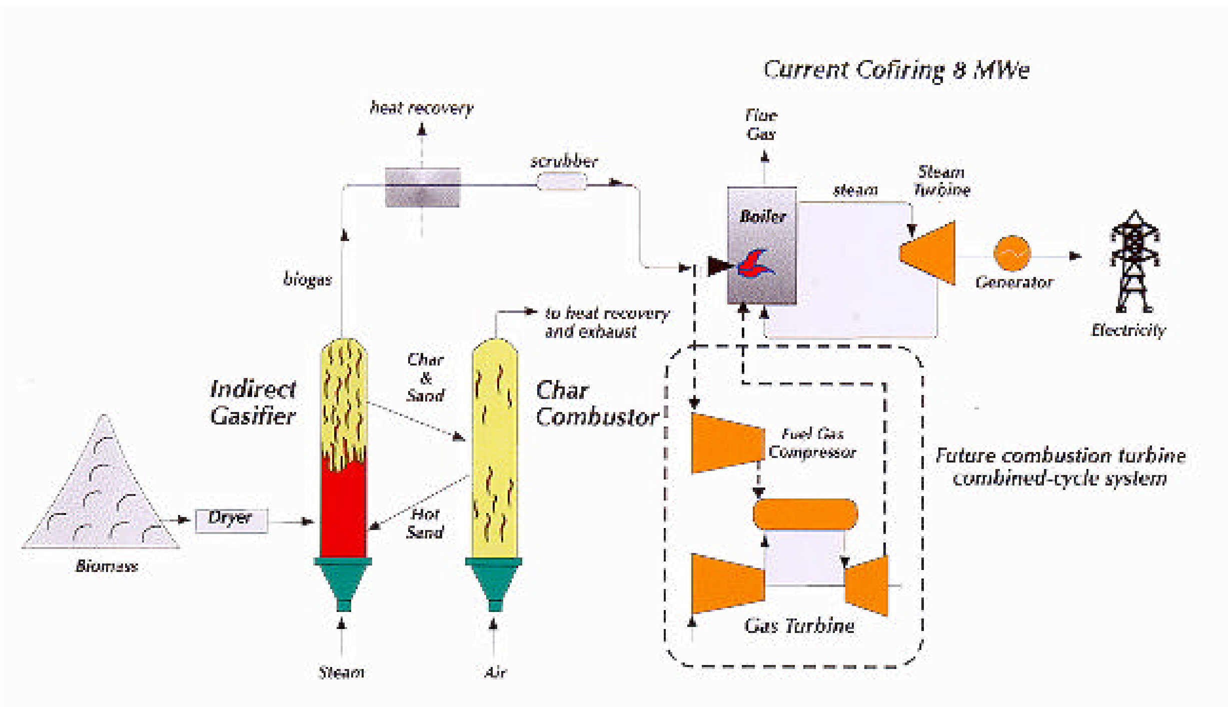


**Figure 4. Schematic of an indirect gasification concept constructed at the McNeil Station, Burlington, VT**

resource depletion, and energy consumption of all processes involved. We start with the transformation of raw materials into building blocks, such as cement and steel for building the power plant, natural gas and other starting materials for fertilizers, and petroleum for diesel. We also consider the final disposal of all products and by-products at the end of their service life. There are three components of a life cycle analysis: 1) Inventory to quantify the energy and material requirements, air and water emissions, and solid waste from all process stages; 2) Impact assessment to examine the environmental and human health effects associated with the emissions and waste products quantified in the inventory stage; and 3) Improvement assessment to propose ways to minimize environmental drawbacks.

This life cycle analytical effort looks at the entire cycle from seedlings to the emissions from the production of the plant biomass, construction of the power plant, and emissions from operations at all phases over the 37 years of construction, operation, and decommissioning. It concludes that biomass electricity might indeed contribute significantly to U.S. energy supplies while minimizing environmental consequences. Compared to regular annual crop farming the use of short rotation poplar wood requires much less fertilizers, herbicides, and water. The biomass electricity system analyzed is nearly closed from a carbon cycling point of view. The net energy ratio is 16:1—sixteen times more "green" energy is produced per unit of fossil fuel consumed (Figure 5).

Several independent scenarios of world energy evolution indicate that by 2050, biomass has the potential to contribute 25–50% of the present global energy. Shell International Petroleum Co. scenario calculations (1994–96) indicate certain assumptions in which new biomass sources could contribute 45–50%.[23] These careful evaluations have been followed by the creation of Shell International Renewables (1997) with major investments in biomass forestry and biomass power generation. The second assessment report of the Intergovernmental Panel on Climate Change[24] identified biomass as a major contributor (25–45%) by 2050. Ecologically driven scenarios of the World Energy Council (1996) come to similar conclusions.[6] The President's Committee of Advisors on Science and Technology report on Federal Energy Research and Development for the Challenges of the 21st Century (1997) recognizes that biomass is one of the major contributors to global energy and has many other environmental, social, and economic benefits.[24]

The arrival of a transnational company capable of implementing these technologies in many countries is noteworthy. Shell International Renewables is implementing Royal Dutch Shell's fifth business line. In addition to PV energy as an area of business, short rotation forestry and biomass electricity are part of this new line of business. The company is interested both in the large-scale activities and in the small scale which would allow them to implement Sun Stations.[25] In this concept, short rotation forestry plantations are established near a village. The village has a small biomass power station to supply electricity to grid connected homes. Just like a gas station, the sun station model could be easily duplicated worldwide and serviced from a centralized or decentralized structure. PV energy provides electricity to the homes distant from the center of the village and backup energy for critical operations. As a company like Shell operates in more than 130 countries, it is easy to see how this powerful concept could dominate many rural areas in the future while providing a high quality of life to a rural population. These renewable-energy self-sufficient towns—the "sun towns" could develop throughout the world coupling energy and forest products activities.

## Solar Thermal[1,2,26]

Solar thermal systems convert energy from sunlight to thermal energy, which can either be used directly as heat energy or converted into electricity. Three solar thermal electric

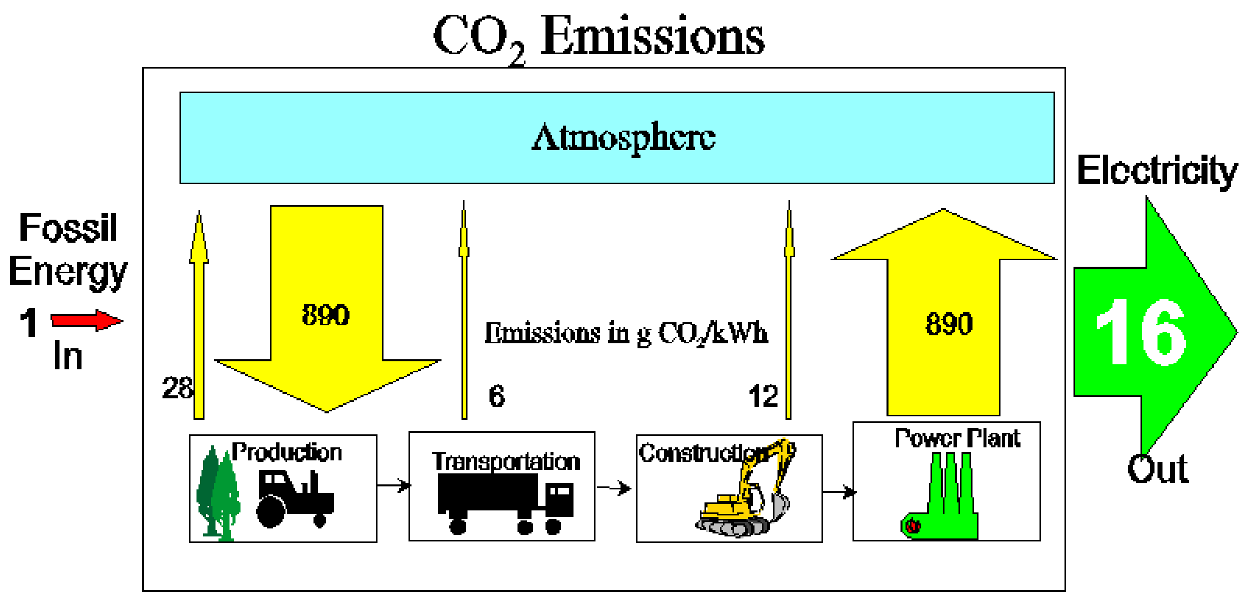


**Figure 5. Life cycle analysis of a dedicated hybrid poplar agroforestry farm supplying an integrated gasification combined cycle using indirect gasification (see Fig. 4)**

technologies—parabolic troughs, central receivers, and parabolic dishes—are being developed in the U.S. today. All three technologies use tracking mirrors to reflect and concentrate sunlight onto a central receiver, where the conversion to high temperature thermal energy takes place.

Over the last decade, the U.S. solar thermal industry has established a track record in the power industry by building and operating utility-scale power plants with a combined rated capacity of 354 MW. The technology used in these power plants is based on years of R&D, much of it sponsored by DOE. Two new solar technologies—power towers and dish/engines are the focal point of the current program.

## Area Requirements for Selected Renewable Energy Technologies

The approximate yearly electricity delivered by four renewable energy technology concepts on a unit land area basis are compared in Table 1. R&D on improving the efficiency of conversion would decrease the land requirements. Geothermal and biomass power provide base load power, whereas wind and PV energy are intermittent.

**Table 1. Comparison of renewable energy delivery per unit land area**

| Resource | Annual Delivered Energy $kWh/m^2$ |
|---|---|
| Wind (intermittent) | 11 (average wind speed)<br>18 (high wind speed) |
| Biomass (base load) | 15 (low efficiency)<br>45 (high efficiency) |
| Photovoltaic (intermittent) | 50-100 |
| Geothermal (The Geysers) (base load) | 160-200 (1995 data) |

Average wind speed, class 4, 6–7.5 m/s
High wind speed, class 6, 7–8.8 m/s

## The Economic Potential of Renewable Energy Systems

We compare the economic potential for renewable energy systems in Tables 2 and 3.[2,3] In a direct comparison with very inexpensive sources such as natural gas using combined cycle technology for electricity production, electricity from renewable technologies is still more expensive today in spite of excellent progress achieved in the past twenty years. Only in specific niches are renewable energy technologies cost-competitive today. However, when considering the environmental benefits on a life cycle basis, the renewable energy option excels. Our society has not yet found acceptable ways to incorporate these externalities into the cost of our energy. Some of the environment, energy resources, economics, and employment viewpoints on renewables and externalities are discussed in references 27 and 28.

**Table 2. Economic potential of renewable energy systems**

| Technology | Current Estimated Cost | | | Estimated Cost of Next Generation | | |
|---|---|---|---|---|---|---|
| | Capital $/kW | Operating Cent/kWh | Total Cent/kWh | Capital $/kW | Operating Cent/kWh | Total Cent/kWh |
| Photovoltaic Systems | 7000 | NA | 25-35 | 3000-5000 | NA | 15 or less |
| Biomass Power | 1700-2000* | 4.5-5.5 | 7-15 | 1000 | 0.5-1.0 | 4-6 |
| Wind Power | 900-1400 | 1.0-2.0 | 5-10 | 760-1000 | .5-1.0 | 4-7 |
| Geothermal (hydrothermal) | 1500 | 2.0-2.5 | 7-10 | 900-1000 | 1.5 | 4 |
| Solar Thermal Power | 3000 | 2.0 | 20-25 | 1500-3000 | 1.8 | 6-8 |

*Cofiring biomass with coal is a less capital intensive route to generate electricity.

A comparison of renewable energy technologies, their markets, and timeframe to reach those markets are shown in Table 3. Some of the constraining and facilitating factors are identified as well as overall marketability of these technologies. Overall, the ongoing utility restructuring makes it more difficult for these technologies to penetrate unless a renewables portfolio standard or other policy measure is implemented to continue to encourage renewable energy penetration in the U.S. The U.S. government utility restructuring proposal is found in reference 29.

The Renewables Portfolio Standard is a market-based mechanism for ensuring a minimum level of renewable energy development in the electricity portfolios of power suppliers in an implementing jurisdiction (e.g., a state). As originally proposed by the American Wind Energy Association, it would include the creation of a secondary market of tradable certified renewables credits. Sellers could meet their obligation through direct ownership of renewable generation, contracts for power from renewable generating facilities, or purchase of credits for sufficient renewable kWh in the secondary market.[30]

There are many possible variations for implementation of the Renewables Portfolio Standard. Fundamentally, the minimum renewables obligation could be placed either on distribution companies subject to state utility regulations, or on all retail suppliers—including direct access generators selling at retail, municipal utilities, and market aggregators—under an industry structure allowing retail competition.[30] Other alternatives include setting a specific desired proportion of renewables in the energy mix at some point in the future. This pathway was chosen by Australia.

**Table 3. Economic potential of renewable energy systems**

| Technology | Nature of Market | Timeframe for Major Market | Constraining Factors | Facilitating Factors | Marketability |
|---|---|---|---|---|---|
| Photovoltaic Systems | Buildings, utilities, industry and applications | 5–15+ | Economic & institutional | Energy prices & niche markets | H |
| | Off-grid | 0–5 | | | H |
| Biomass Power | Pulp & Paper and Food Processing industries and utilities | 0–5<br>5–10<br>10–15+ | Economic & institutional. Overcoming the learning curve of the first few new technology plants | Regulatory & environmental & need for capital replacement | H |
| Wind Power | Utility and Off-grid | 0–5 | Economic & institutional | Energy prices & modular designs | H |
| Geothermal (hydrothermal) | Hydrothermal | 0–5 | Economic & technical | Energy prices & modularity | M |
| | Hot Dry Rock | 10–15+ | Technical & capital cost | Energy security | L |
| Solar Thermal Power | Utility & industry applications | 5–15+ | Economic & institutional | Energy prices<br>modularity<br>niche markets | H |

Notes: L, M, H = Low, Medium, and High marketability.

Overseas, significant new generating capacity will be needed in developing countries in the coming years. About 60% of current worldwide capacity additions for energy supply will be installed in developing countries in the near term. Renewable energy has a very good chance to penetrate these global markets. Because the proportion of direct foreign investment by the private sector will increasingly be larger than that by world governments, the private sector will have a major role in deciding which technologies will be implemented in the 21st century and an impact on the selected infrastructure of developing countries. In this unfolding economic scenario, renewable energy technology investments are more likely to be made by the private sector. Investments in nuclear energy, on the other hand, still require significant government participation.

## Conclusion

Two decades of R&D progress have set renewable energy technology on pathways to commercialization and diffusion. R&D resulted in significant cost reductions. The renewable energy technologies commercial successes and failures are establishing a track record in technology cost and performance. As a result, capital markets are becoming more familiar with the benefits and risks of these investments. Growing awareness of the new opportunities presented by renewable energy technologies, particularly in developing countries, has generated much interest in, and intense competition from, European and Asian countries and companies. The trend of transnational companies increasingly investing in the renewable energy technologies bodes well for the field for many countries throughout the world. They may be hedging their bets as to which energy areas will succeed in the future but technological winners will continue to emerge. As those technologies become commercial realities, our environment, our ecological life support systems, and our future generations will benefit from the persistence and creativity of researchers, visionaries in government and in the private sector, and the people for their support of these technologies.

**Note**: After this paper was written, the *Economist*, a world-renowned magazine published the article "When Virtue Pays a Premium" in its business section (April 18, 1998, pp. 57-58). The article independently reflects the considerations described in this paper. In the same issue the *Economist* discusses cleaner energy reflecting support for renewables and how the world is treating various incentives.

## Acknowledgments

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# Climate Change and the Future of Nuclear Energy

Steve Fetter

## Introduction

In December, world attention turned to Kyoto, Japan, where parties to the Framework Convention on Climate Change negotiated a protocol to reduce the greenhouse gas emissions of the industrialized countries to five percent below 1990 levels by 2008-20012. The agreement was attacked from both sides, with environmental groups claiming that deeper reductions are urgently needed, and opponents claiming that reductions are unnecessary and would curtail economic growth.

The current focus on near-term reductions is misguided. Deep reductions in the emissions of the industrialized countries over the next ten or twenty years would be costly, but would not go very far toward achieving the ultimate objective of the Climate Convention. The modest reductions called for by the Kyoto agreement are a prudent first step, but only if they are part of a larger, long-term strategy. The centerpiece of any strategy to achieve the objective of Climate Convention is a transformation in world energy supply (beginning no later than 10 or 20 years from now) in which traditional fossil fuels are replaced by energy sources that do not emit carbon dioxide.

Of the energy sources that are technically feasible today, only fission, solar, and decarbonized fossil fuels, and, to a lesser extent, biomass and wind, are capable of supplying a substantial fraction of future world energy demand without significant carbon dioxide emissions. All of these sources now have serious economic or environmental shortcomings. Nuclear fission, which is the only one that is deployed commercially on a large scale today, suffers from concerns about high cost, accident and waste disposal risks, and potential links to the spread of nuclear weapons. The most urgent need, therefore, is a broad-based program of energy research and development to attempt to ameliorate these concerns, and thereby ensure that inexpensive and acceptable substitutes will be available worldwide when they are needed.

## The Objective of Emission Controls

The objective of the Climate Convention is to achieve “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”[1] The level that would prevent “dangerous interference” is undefined, but the Convention states that stabilization “should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

Most studies of climate change focus on the effects of a doubling of the carbon dioxide concentration from the preindustrial level of about 280 ppm. According to the IPCC, a doubling would, over the long term, increase the global-average surface air temperature by 1.5 to 4.5 °C, with a best estimate of 2.5 °C.[2] The wide range is due largely to uncertainties about how clouds would change as the atmosphere warmed. More important than changes in average global temperature, but even more difficult to predict, are regional changes in seasonal temperature, precipitation, soil moisture, and in the frequency of extreme events such as storms and drought.

In general, average temperature increases in northern continental regions are expected to be twice the global average. Average precipitation is predicted to increase by 5 to 15%, but some regions, such as the northern mid-latitudes, are expected to become drier in the summer because of even greater increases in evaporation.[3]

Would these changes constitute "dangerous interference" with the climate system? One way to gain insight is to examine past changes in climate. Figure 1 shows how the average temperature of the earth has varied over the last million years. Also shown are estimates of future changes expected in a "business-as-usual" scenario in which greenhouse gas concentrations reach an equivalent doubling by 2070 and continue to rise thereafter. Several features of this temperature history deserve special attention.

First, global-average temperature has increased by about 0.5 °C over the last 100 years, consistent with estimates based on the increase in greenhouse gases during this period. The last decade is the warmest period since at least the 14$^{th}$ century, and one of the warmest in the last 10,000 years.

Second, average temperature has been relatively stable for the last 10,000 years, with variations up or down of only about 1 °C. This period of stable climate coincides with the development of agriculture and human civilization. However, even these small variations in global-average temperature were associated with significant changes in regional climate that had important consequences for ecosystems and human societies. For example, 4000 to 6000 years ago, when global-average temperature was about 1 °C higher than at present, the tropics were wetter and experienced catastrophic floods four-to-ten times greater than those witnessed today, and temperate latitudes were significantly drier.[4] Between 1100 and 1300 AD, when temperatures in Europe were about 1 °C higher than at present, the Vikings colonized Greenland; the subsequent cool period, when average temperatures in Europe and China were 0.5 to 1 °C lower than at present, was accompanied by violent storms and floods, crop failures, widespread famine, and devastating epidemics.[5]

Third, over the last two million years the climate has oscillated between long ice ages and shorter interglacial periods, with a period of about 100,000 years. During the last Ice Age, average temperatures and sea levels were about 5 °C and 120 m lower than at present; during the last interglacial period, temperatures and sea levels were about 2 °C and 5 m higher than present. These changes in temperature, which were accompanied by dramatic shifts in the distribution of vegetation, are comparable to that which would accompany a doubling of the carbon dioxide concentration.

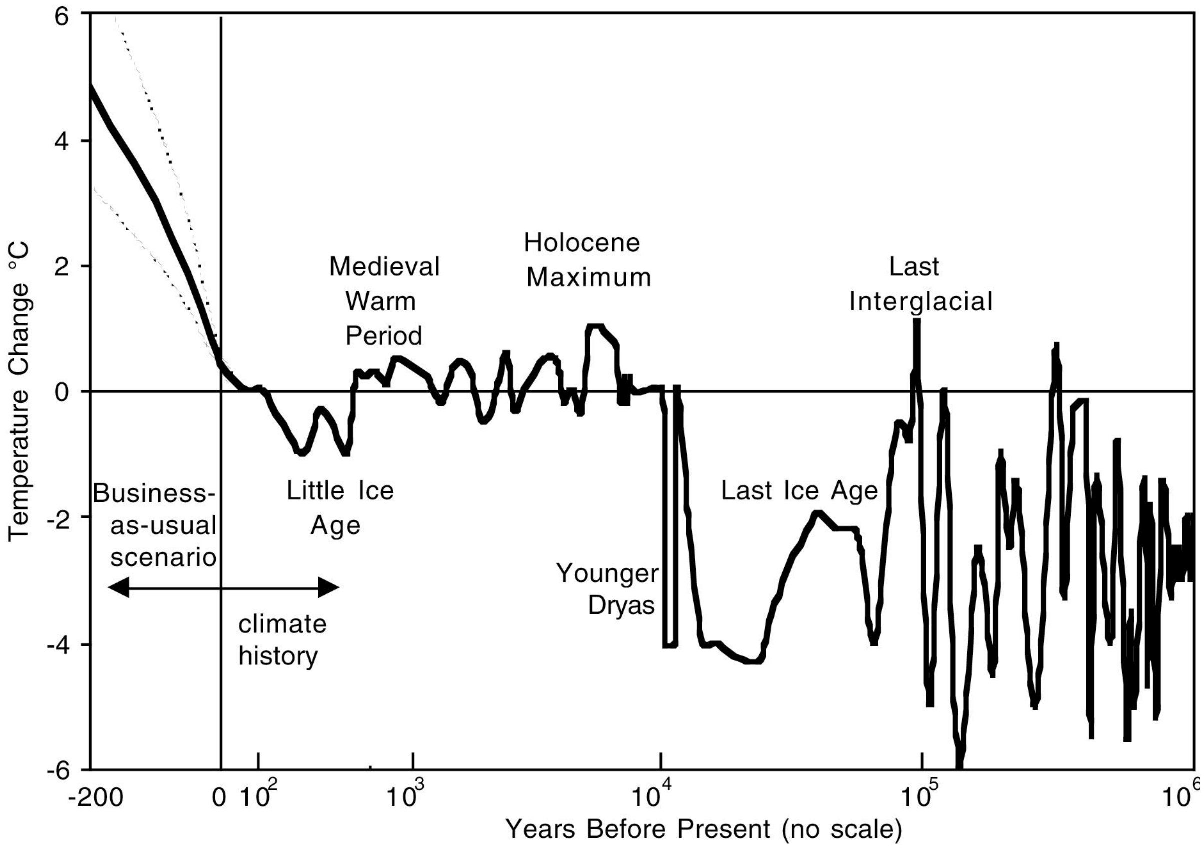


**Figure 1. Global-average surface temperature change over the last million years, and projected change to 2200 under a "business-as-usual" scenario**

**Source: L.A. Frakes, *Climates throughout Geologic Time* (Amsterdam: Elsevier, 1979).**

Glacial periods are correlated with known variations in the Earth's orbit, which change the amount of summer sunshine received by the poles. These variations in sunshine are too small by themselves to account for the observed changes in climate. There must exist strong feedback mechanisms in the climate system—for example, changes in the biosphere or ocean currents—which serve to amplify the warming caused by increased sunshine. The sensitivity of the climate system to past variations in sunshine should make us wary about its sensitivity to changes in the radiation balance caused by increased greenhouse gas concentrations.

Fourth, past shifts in climate sometimes have been very rapid. For example, there were about two dozen instances during the last Ice Age when temperatures rose or fell by up to 5 °C over periods of less than a few decades. As the Earth emerged from the last Ice Age 13,000 y ago, the climate suddenly returned to Ice Age conditions; 1300 y later, a warming in the Arctic of about 7 °C occurred over about 50 y, after which the current warm climate has prevailed.[6] These rapid shifts in climate might have been caused by a switching on and off of the North Atlantic thermohaline circulation, which today transports huge quantities of heat northward, keeping Europe much warmer than other regions of the same latitude. These episodes alert us to the possibility that rapid, large-scale changes in climate might be triggered if temperatures increase beyond some threshold. Although the threshold, if one exists, is unknown, it might be no greater than the upper range of the temperature increase predicted for a doubling of carbon dioxide.[7]

Another way to gain insight into how much change would be dangerous is to model the effects of climate change on ecosystems, agriculture, and economies. In general, an increase in carbon-dioxide concentrations, and the associated increase in global average temperature and precipitation, should promote plant growth except in areas where the additional precipitation does not compensate for the increase in evaporation. Under the conditions predicted by climate models for a doubling of carbon dioxide concentration, models indicate that present-day vegetation patterns would remain stable for an average of only 60% of the world's surface area. Current vegetation boundaries would shift by 300 to 1,000 kilometers, greatly outstripping the ability of most species to migrate naturally.[8] Rising sea levels will also cause wetlands to be lost at a faster rate than new wetlands would be created.

The capacity of human societies to modify agricultural practices in response to changes in climate is much greater than during previous periods of change, particularly in developed countries. One study concluded that, for climate conditions predicted in 2060 under a "business-as-usual" scenario, total world grain production would decline by up to 5%, compared to what it would have been without climate change.[9] With a greater degree of adaptation (e.g., changes in crops and additional irrigation), the study concluded that global harvests could be maintained at no-climate-change levels. Climate changes are, however, projected to have a greater negative effect on production in developing countries, which could lead to shortages in countries that cannot afford to buy grain on world markets. In addition, the study did not consider the possible effects of increases in climate variability or rapid changes in climate.

Much attention has been given to the economic costs of climate change and of mitigating greenhouse gas emissions. Most studies include the costs associated with sea-level rise, forest and fishery losses, and changes in agriculture, energy demand, hurricane damage, and water supply, but ignore or underestimate impacts that are difficult to monetize, such as the value of ecosystem and species loss, air and water pollution, and human death, illness, discomfort, and aesthetics. As with studies of ecosystem and agricultural impacts, cost studies generally have not considered the effects of possible increases in climate variability or rapid changes in climate.

With these caveats in mind, the expected cost of impacts associated with a 2.5 °C average temperature increase is estimated at 1 to 2% of GDP for developed countries, 2 to 9% for developing countries, and about 2% for the world as a whole.[10] For some countries, such as low-lying islands, losses could be a much greater percentage of GDP. For comparison, 2% of current GWP is over $500 billion per year.

There is, of course, great uncertainty in these estimates. In a poll of 19 experts, best guesses of the cost of a 3° warming by 2090 centered around 2% GWP, but ranged from 0 to 21%.[11] Half believed that there is at least a 10% chance that the cost would be greater than 6% of GWP. The average respondent believed that costs would triple if the average temperature increase were 6 °C instead of 3 °C, and that there would be a 5% chance of a 25% drop in GWP—the rough equivalent of the Great Depression.

## Selecting a Stabilization Target

One way to develop a strategy is to construct reasonable scenarios and to ask what we should be doing today if these scenarios were to become reality. We do not know very accurately how climate will change in response to increased greenhouse-gas concentrations, or how natural systems and human societies will be affected by changes in climate. But it is worthwhile to set tentative limits on greenhouse gas concentrations based on the current state of knowledge, trace the implications of such limits for the future of world energy supply, and to ask what we should be doing today to prepare for these changes.

Based on what we know today, it would be difficult to justify a stabilization target greater than an equivalent doubling of carbon dioxide, to 560 ppm. Stabilization at this level would result in an increase in average temperature of 1 to 2.5 °C over the next century, and a total increase of 1.5 to 4.5 °C. At the upper end of this range, substantial and costly changes in climate would be certain, and the risk of catastrophic changes would be substantial. Even the "best estimate" change in temperature—2.5 °C total and 1.5 °C over the next century—would entail significant risk of costly changes in climate, particularly in the northern regions.

Stabilization targets are sometimes expressed in terms of "radiative forcing," or the change in the energy balance of the climate system that would result from an instantaneous increase in greenhouse gas concentrations. A doubling of carbon dioxide produces a radiative forcing of 4.4 $W/m^2$. An "equivalent" carbon dioxide concentration is the concentration of carbon dioxide that would produce the same radiative forcing (and therefore the same climate effects) as a given mixture of greenhouse gases. Any combination of greenhouse gases that resulted in a radiative forcing of 4.4 $W/m^2$ would represent an "equivalent doubling" of carbon dioxide.[1]

Over the last 150 years, deforestation and the burning of fossil fuels have increased the concentration of carbon dioxide from about 280 ppm to 363 ppm. The total radiative forcing, including contributions from other long-lived greenhouse gases, is 2.6 $W/m^2$, which is equivalent to a carbon-dioxide concentration of about 420 ppm.[12] Thus, we already are halfway toward an equivalent doubling of carbon dioxideg.

[1] The radiative forcing $\Delta F_{CO_2}$ associated with a carbon dioxide concentration C is given by $\Delta F_{CO_2} = 6.3 \ln (C/C_O)$ $W/m^2$, where $C_O$, the preindustrial concentration of carbon dioxide, is 280 ppm. The equivalent carbon dioxide concentration is given by $C[eq] = 280 \exp (\Delta F/6.3)$ ppm, where $\Delta F$ is the radiative forcing due to all greenhouse gases.

## Limits on Fossil-Fuel Emissions

To translate a stabilization target into a limit on global emissions of carbon dioxide from the burning of fossil fuels, we must subtract the long-term radiative forcing of greenhouse gases other than carbon dioxide, use carbon-cycle models to determine rates of emission that lead to stabilization at the desired level, and account for carbon dioxide emissions from other sources, such as land-use changes and cement manufacture.

### Other Greenhouse Gases

Carbon dioxide is the most important greenhouse gas, and it is more amenable to monitoring and control than other gases. We must, however, take into account emissions of methane, nitrous oxide, and halocarbons, which also exert a long-term influence on climate. Increased concentrations of these gases currently are responsible for a radiative forcing of 0.9 $W/m^2$, equivalent to an additional 60 ppm of carbon dioxide. The long-term contribution of ozone and various aerosols can be ignored. [13]

Anthropogenic emissions of methane and nitrous oxide are due primarily to agricultural and waste disposal activities. Strategies exist for reducing methane and nitrous oxide emissions from most identified sources, but the practical potential for reductions is limited. For example, the largest source of methane emissions—domestic livestock—could be reduced by 20-to-40% through improvements in feeding and manure management,[14] but such reductions will be more than offset by an increase in the number of animals. Similar arguments can be made for most other anthropogenic sources of methane and nitrous oxide, and it is also possible that natural emissions of these gases may increase as a result of climate change. Thus, even if aggressive efforts are made to limit emissions of methane and nitrous oxide, significant reductions in long-term, global emissions are not likely. If rates of emission remain constant at today's levels, the combined radiative forcing of these two gases would increase from 0.65 $W/m^2$ to about 1.0 $W/m^2$.[15]

Halocarbons also contribute to greenhouse warming. Although the Montreal Protocol and its Amendments will lead to a phase-out of substances containing chlorine and bromine, their residence times are so large that significant concentrations will remain in the atmosphere for over a hundred years. In addition, many CFC-substitutes, as well as a number of other unregulated substances, are greenhouse gases. Today, the forcing from halocarbons and other trace gases is about 0.28 $W/m^2$; long-term values might be somewhat lower or higher.

For stabilization at an equivalent doubling of carbon dioxide, gases other than carbon dioxide are likely to contribute a radiative forcing of about 1.3 $W/m^2$. Carbon dioxide would then be limited to a forcing of 3.1 $W/m^2$ and a concentration of about 460 ppm. It is possible, but highly unlikely, that other greenhouse gases could be limited to a long-term forcing of 0.8 $W/m^2$, in which case the carbon dioxide concentration could be as high as 490 ppm under an equivalent doubling.

### Carbon Emissions

Carbon dioxide emitted into the atmosphere is gradually absorbed by the oceans and by plants. Carbon-cycle models, which simulate these processes, can be used to estimate the rates of emission that would result in stabilization of the carbon dioxide concentration at a given level. Figure 2 shows the rate of emission over the next 150 years for stabilization at 450 and 500 ppm (the dark red and blue lines, respectively). The uncertainty in the emission pathway, which is mostly due to uncertainties about the fertilization of plant growth, is indicated for the 450 ppm case by the narrow red lines. Also shown are emissions for a more gradual approach to

450 ppm and for a more rapid approach to 500 ppm (the light red and blue lines, respectively). Two features of this figure are worthy of attention.

First, carbon-dioxide emissions must peak no later than 2020. This conclusion is insensitive to assumptions about other greenhouse gases, the rate at which stabilization is achieved, or model parameters. After peaking, carbon-dioxide emissions must decline to levels below the current rate of emission (about 7.5 PgC / y) by 2050, and to no more than half that rate by 2100.

Second, the stabilized concentration of carbon dioxide is determined primarily by the rate of emission in the second half of the next century. A slower approach to stabilization would

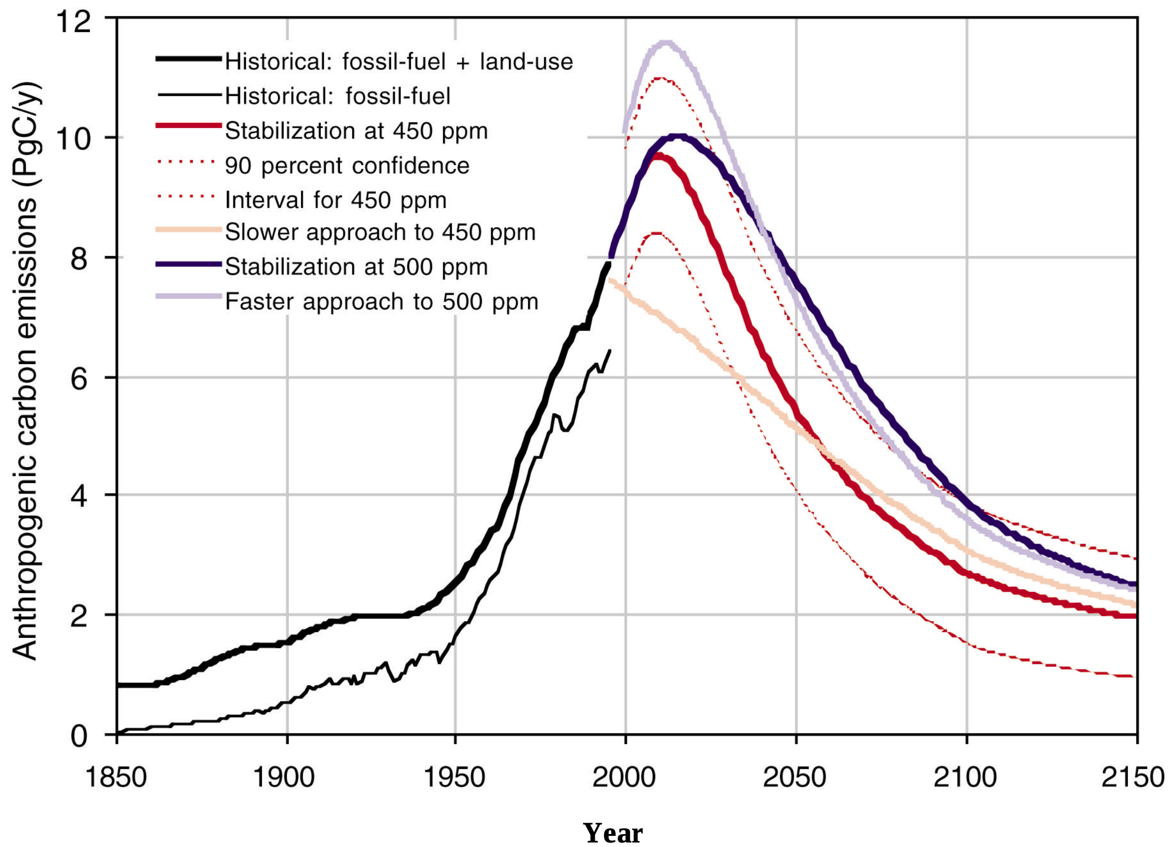


**Figure 2. Historical emissions of carbon from fossil-fuel burning and land-use changes, and emission pathways that stabilize carbon dioxide concentrations at 450 and 500 ppm in the period 2100 to 2150**

**Source: Author's calculations based on results from the model described in T.M.L. Wigley, "Balancing the Carbon Budget: Implications for projections of Future Carbon Concentration Changes," *Tellus*, Vol. 45B, pp. 405–425.**

require immediate reductions in emissions, but would permit only slightly higher emissions over the long term. Conversely, a more rapid approach to stabilization would allow much higher emissions in the near term at the expense of slightly lower emissions over the long term. The total amount of carbon dioxide that can be emitted over the next 100 to 150 y is larger for a more rapid approach to stabilization because near-term carbon emissions will largely be absorbed by the oceans and the biosphere by the time stabilization is achieved. In other words, emissions can be allowed to increase substantially over the next 10 to 20 y, as long as they are reduced below the current level by 2050.

This observation has important policy implications. The stabilization target can, to a first approximation, be translated into a target for total carbon emissions in 2050. Near-term reductions in emissions are important only insofar as they help achieve the target in 2050. In general, it is probably better to invest money in future reductions (via energy research and development) than to pay for costly reductions today.[16]

## Other Carbon Emissions

Anthropogenic carbon-dioxide emissions are due mostly to fossil-fuel burning, but deforestation and cement manufacture also make significant contributions. During the 1980s, it is estimated that tropical deforestation released an average of 1.6 PgC / y and that regrowth of temperate forests absorbed 0.5 PgC / y, for a net rate of emission of 1.1 ± 0.7 PgC / y.[17]

Future emissions from land-use changes are a matter of speculation. Reference scenarios developed by the IPCC and others assume rates ranging from 0 to 2 PgC / y in 2050. [18] On the other hand, scenarios that assume strong policy efforts to slow tropical deforestation and implement reforestation programs result in a net uptake of carbon of 0.5 to 2.2 PgC / y in 2050. [19] All scenarios converge on near-zero net rates of emission in 2100, because the potential for either deforestation or reforestation eventually would be exhausted.

It is possible that climate change itself might cause large transient releases of carbon during the next century. For example, mature forests may die before they are replaced by new forests, and the amount of carbon stored in northern soils may decrease as higher temperatures promote decay. It is estimated that such processes might result in the release of 0 to 240 PgC over the next century, at rates of up to 3 PgC / y during the middle of the next century. [20]

One-half ton of carbon dioxide is released during the production of a ton of cement, as calcium carbonate is converted into lime. In 1995, cement manufacture released 0.2 PgC. By 2050, this could be expected to increase to at least 0.5 PgC / y.

## Fossil-Fuel Emissions

Emissions of carbon from fossil-fuel burning have risen steadily over the last half century, from about 1.4 PgC in 1945 to 6.2 PgC in 1995—an average growth rate of 3% per year. [21] Including other sources of carbon, total anthropogenic emissions were about 7.5 ± 0.9 PgC in 1995.

In order to stabilize greenhouse gas concentrations at an equivalent doubling, fossil-fuel emissions of carbon dioxide must be limited to 6 ± 2 PgC / y in 2050 and 2.8 ± 1.2 PgC / y in 2100. These limits take into account the long-term contribution of other greenhouse gases, other sources of carbon dioxide, and uncertainties in these and other parameters.[22]

Limits on carbon emissions can be translated into limits on traditional fossil energy supply by noting that 1 EJ of fossil energy releases 17 to 20 TgC, depending on the mix of coal, oil, and gas. The limits on fossil-fuel carbon emissions therefore translate into 330 ± 110 EJ/y in 2050, and 150 ± 70 EJ/y in 2100.

## Future Energy Demand

The demand for energy will grow substantially over the next century, driven by increases in both population and per-capita consumption in developing countries. Figure 3 shows several scenarios of future energy consumption. These scenarios generally assume no policy-driven market interventions, such as carbon taxes, but they do account for expected improvements in energy efficiency and price increases caused by the depletion of oil and gas resources. Estimates of world primary energy consumption range from 590 to 1260 EJ/y in 2050, and from 620 to 2800 EJ/y in 2100.

By subtracting the limits on fossil-fuel supply from the total energy demand, we derive requirements for non-carbon-emitting energy supply.[23] These are given in Table 1 for stabilization at an equivalent doubling of carbon dioxide. Note that the supply of energy from

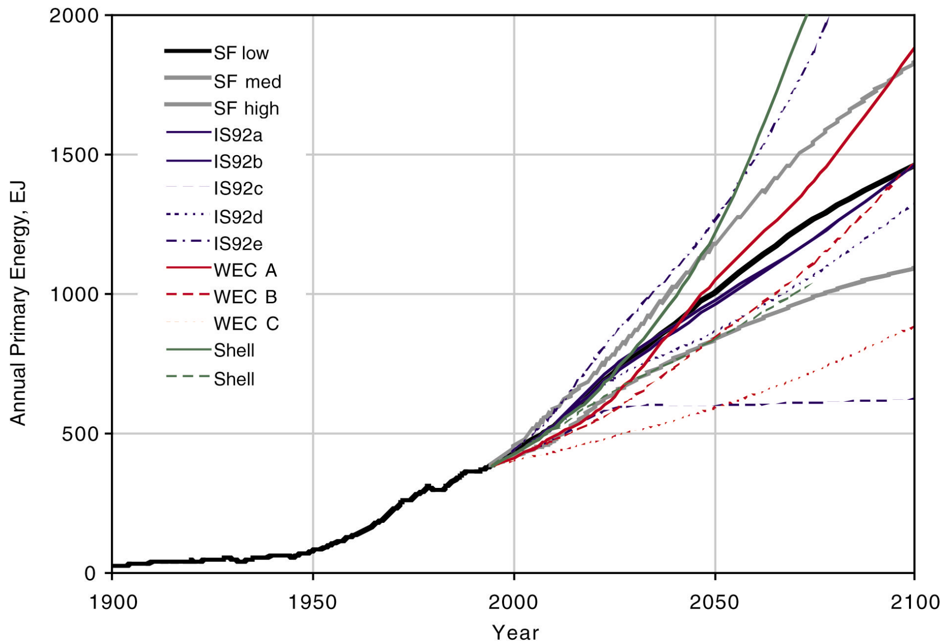


**Figure 3. Scenarios of future world commercial primary energy consumption by Fetter (SF), the Intergovernmental Panel on Climate Change (IS92), the World Energy Council (WEC), and Shell Oil**

**Sources: Steve Fetter, *Climate Change and the Tranformation in World Energy Supply* (to be published) J. Leggett, W.J.Pepper, and R.J. Swart, "Emission Scenarios for IPCC: An Update," in J.T. Houghton, B.A. Callander and S.K. Varney, eds., *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (Cambridge: Cambridge University Press, 1992); World Energy Council and International Institute of Applied Systems Analysis, *Global Energy Perspectives to 2050 and Beyond* (London: WEC, 1995); and Shell International Ltd., *The Evolution of the World's Energy Systems* (London: Shell Intrnational, 1996).**

sources that do not emit carbon must grow from 53 EJ / y in 1995 to roughly 600 EJ / y by 2050—an average growth rate of nearly 5% / y.

**Table 1. Characteristics of world commercial primary energy supply for stabilization at an equivalent doubling of carbon dioxide**

| | Commercial Primary Energy Supply (EJ/y) | | | |
|---|---|---|---|---|
| Year | Total | Traditional Fossil | Non-$CO_2$-Emitting | Growth Rate of Non-$CO_2$ Supply (%/y) |
| 1995 | 382 | 329 | 53 | 2[a] |
| 2050 | 930 ± 280 | 330 ± 110 | 600 ± 300 | 3–5[b] |
| 2100 | 1450 ± 600 | 150 ± 70 | 1300 ± 600 | 1–2[c] |

Sources: Figures 2–3 and author's calculations. Growth rates of non-$CO_2$-emitting resources correspond to the periods: a. 1995; b. 1995–2050; c. 2050–2100.

The implications of this scenario for world energy supply are profound. Today, fossil fuels supply 86% of commercial energy supply. If greenhouse gases are to be stabilized at an equivalent doubling, traditional fossil fuels can supply no more energy in 2050 than they supply today, even while total energy use doubles or triples. Non-carbon-emitting sources must grow from 14% of total commercial supply to 50–80% of total supply in 2050.

The transition to non-carbon-emitting sources will be the third transformation in world energy supply. The first shift, from firewood to coal, took place from 1850 to 1900. The second shift, from coal to oil and gas, took place from 1925 to 1975. In these first two shifts, it took 50 years for the dominant source to go from 10 to 60% of total supply. The third major shift, from fossil fuels to non-carbon-emitting sources, will occur from 2000 to 2050—if, that is, we decide to take seriously the task of preventing dangerous interference with the climate system.

## Non-Carbon-Emitting Energy Sources

In 1995, non-fossil sources supplied about 53 EJ of primary commercial energy: 27 EJ from hydropower, 25 EJ from nuclear fission, and 1.2 EJ from geothermal, wind, biomass, and solar. Another 54 EJ was supplied by noncommercial biomass—fuelwood and dung—but much of the fuelwood was harvested in an unsustainable manner, resulting in deforestation and a net release of carbon dioxide.

For stabilization at an equivalent doubling, non-carbon-emitting sources must supply 600 ± 300 EJ / y of primary commercial energy by 2050. Only five sources are capable of supplying a substantial fraction of this non-carbon supply: solar, fission, decarbonized coal, and, to a lesser extent, biomass and wind. Other potential sources are either too limited (hydropower and hot-water geothermal), too expensive (ocean thermal and wave energy), or too unproven (fusion and hot-rock geothermal) to make a substantial contribution by 2050.

Each of the major alternatives currently has significant economic, technical, and / or environmental handicaps. Solar is environmentally benign, but the cost of photovoltaic electricity is currently more than five times greater than that of coal-fired electricity. Moreover, solar would require massive and inexpensive energy storage if it is to supply more than 10% of energy demand. Nuclear fission can produce electricity at prices competitive with coal, but it suffers from public-acceptance problems related to the risks of accidents, waste disposal, and the spread of nuclear weapons. Coal is abundant and can be converted into either electricity or portable fuels, but the cost and environmental impact of capturing, transporting, and disposing of the carbon dioxide could be high. Biomass also has the potential to supply low-cost portable fuels, but generating large quantities of biofuels would require vast areas of land, in competition both with agriculture and the preservation of natural ecosystems. Wind is already economically competitive at windy sites close to cities or existing transmission lines, but attractive sites are limited.

The most pressing need, therefore, is research and development aimed at reducing the liabilities of the major alternatives. Last year, the U.S. government spent a little more than $1 billion on energy R&D, compared with the $500 billion spent on energy in the United States ($60 billion of which went for imported oil). Total energy R&D—private as well as public—amounted to less than 1% of energy expenditures, compared with an average of 3.5% for all U.S. industries.

In the past, it has taken about 20 years to realize significant commercial benefits from energy research and development. To prepare for—and profit from—the transformation in energy supply that must begin in earnest by 2015, we must do the R&D today. Our options are limited. We are not smart enough to pick sure winners, and the stakes are too high to rule out any major alternative. We need a balanced R&D program that includes substantial investments in all the sources mentioned above, including nuclear fission.

## The Potential Role of Fission

Fission is the only potential major non-carbon source that is deployed commercially on a significant scale today. In 1995, fission supplied 17% of the world's electric power and 6.5% of commercial primary energy. Over the next 50 to100 y, fission could be expanded to provide over half of the world's electric power and a third of the non-carbon-emitting energy supply required to stabilize greenhouse gas concentrations at an equivalent doubling.[24] This is unlikely to happen, however, unless concerns about accidents, waste disposal, and proliferation are resolved.

Most people in the nuclear energy community do not seem to believe that fission's problems are real, in the sense that the problems are regarded as political rather than technical in nature. In their view, current reactor designs are very safe, waste-disposal risks are infinitesimal, proliferation risks are purely theoretical, and costs have been inflated by unjustified licensing delays. They believe that sound technical solutions are already in hand, but worry that the current lack of support for fission might cause expertise to atrophy, particularly in the United States.

Most people in the anti-nuclear community seem to believe that the liabilities of nuclear energy are so great and so intractable that no amount of R&D could solve them. In their view, fission is simply "beyond the pale." They oppose government-sponsored research on fission, believing that it would only divert resources from renewables and prop up an industry that otherwise is headed toward extinction.

The Clinton administration and the Congress seem to agree that fission either does not deserve or does not require government support for research and development. Federal funding for fission-energy R&D has declined from nearly $2 billion in FY78 to a mere $46 million in FY98, with no funds allocated for new reactor concepts. Industry spending has also declined greatly.

Thus, proponents and opponents of fission and budget-cutting politicians have combined to inhibit innovative thinking about the future of fission. This is regrettable, given the potential contribution that fission could make to reducing carbon emissions and stabilizing concentrations of greenhouse gases.

This may be changing. In a recent report on U.S. energy R&D, the President's Committee of Advisors on Science and Technology argued that "given the desirability of stabilizing and reducing greenhouse gas emissions, it is important to establish fission energy as a widely viable and expandable option if this is at all possible. A properly focused R&D effort to address the problems of nuclear fission power—economics, safety, waste, proliferation—is therefore appropriate."[25] The key recommendation is the creation of a Nuclear Energy Research Initiative, funded initially at $50 million per year and increasing over five years to $100 million per year, to fund R&D on safer and lower-cost reactor designs, new waste-disposal techniques, and proliferation-resistant fuel cycles.

The focus of the proposed program is perfect, but the scale of the effort may be too modest. For comparison, the recommended funding for renewables—mostly biomass, solar, and wind—rises from $410 to $570 million per year over the five-year period.[26] Moreover, the Panel recommended that funding for fusion energy—a source which almost certainly will not make a significant contribution to energy supply before 2050—be increased from $250 to 320 million per year. As another point of comparison, the U.S. government spent about $6 billion, in addition to the billions spent by industry, to help develop the light-water reactor.[27] A serious effort to reintroduce fission energy probably would require government support at a rate of several hundred million dollars per year for ten to twenty years.

What types of fission R&D should be supported? First, R&D is needed on reactor designs that are immune to operator error or equipment failures. Current designs are safe if they are built and operated properly, and advanced versions of these designs are even safer. Unfortunately, examples of poor management of nuclear plants abound.

The goal should be to build reactors that cannot produce off-site fatalities, regardless of what happens inside the plant. The Westinghouse AP 600, which is nearing design certification, might meet that standard. There should be room in an expanded energy R&D program to support industry government partnerships on additional advanced designs, such as the Simplified BWR, the MHR-GT, or the Safe Integral Reactor. The concept of small, factory-built modular reactors with lifetime cores is especially interesting.

There is no reason to fund research on breeder reactors for at least the next thirty years. Breeder reactors will be economically attractive only if the price of uranium becomes so high that their increased efficiency of uranium use compensates for their higher capital cost. However, low-cost uranium resources are sufficient to support a very large increase in fission energy over the next century. Exploration, which has virtually ceased over the last 20 years because of low uranium prices, would undoubtedly uncover substantial additional resources if prices rose significantly. It may be possible to extract uranium from seawater for less than $250/kg, in which case breeder reactors may never be necessary or economical. In any case, it would be foolish to tie the expansion of fission over the next 50 or so years to breeder reactors or reprocessing.

Second, the Federal government should support R&D on alternative fuel-cycle concepts designed to minimize proliferation risks in a world with many more reactors, and with reactors in many more countries. This could include novel reactor concepts, such as lifetime cores; new reprocessing techniques that do not involve the separation of pure plutonium; fuel cycles that minimize the production of high-quality plutonium, such as the thorium fuel cycle; the indefinite use of seawater uranium on a once-through fuel cycle; and institutional solutions, such as the consolidation or international control of facilities that handle plutonium fuels.

Third, the Federal government should support R&D on alternative waste disposal concepts. Today, R&D is limited to a single concept—deep geologic disposal—and, in the United States, to a single site—Yucca Mountain. If current waste-disposal concepts experience significant technical or political setbacks, fission is unlikely to expand substantially. Alternatives to Yucca Mountain should be developed—short-term alternatives, such as interim storage, as well as long-term alternatives, including disposal in granite and in the deep sea bed.

## Conclusion

Meeting the objective of the Framework Convention on Climate Change—to prevent dangerous interference with the climate system—will require a fundamental transformation in the nature of world energy supply, beginning in the next 10 to 20 years. Over the next 50 years, the supply of energy by sources that do not emit carbon dioxide must increase ten-fold, from 14% to over 50% of total supply. All of the possible non-carbon-emitting sources have serious drawbacks that must be resolved if they are to play a major role in future energy supply. In the case of fission, we must begin an energetic R&D program to address concerns about accidents, waste-disposal, and proliferation.

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12.. Assumes 1997 concentrations and radiative forcings of 363 ppm and 1.64 W / $m^2$ for carbon dioxide, 1.76 ppm and 0.49 W / $m^2$ for methane, 0.315 ppm and 0.16 W / $m^2$ for nitrous oxide, and a forcing of 0.28 W / $m^2$ for various halocarbons. The equivalent carbon dioxide concentration, $C_{eq}$, is the $CO_2$ concentration that would produce a radiative forcing equal to that from all greenhouse gases (in this case, 1.64 + 0.49 + 0.16 + 0.28 = 2.57 W / $m^2$); $C_{eq} = C_0 e^{\Delta F / 6.3} = (280)e^{(2.57 / 6.3)} = 421$ ppm.

13. First, the influence of ozone and aerosols on climate is highly uncertain. Second, because their residence times in atmosphere are on the order of days, any effect on climate will be regional, not global. Third, ozone and aerosols are generated by the burning of fossil fuels. Stabilizing equivalent carbon-dioxide concentrations at 560 ppm or below will require that fossil-fuel burning be reduced by at least a factor of two below current levels over the long term resulting in proportional decreases in the concentrations of ozone and aerosols. Fourth, efforts to control air pollution and acid deposition will lead to long-term reductions in ozone and aerosol concentrations independent of efforts to limit fossil fuel burning, particularly as pollution-control technologies advance and diffuse to developing countries.

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15. If rates of emission remain constant at today's levels, concentrations would rise from 1.76 to about 1.90 ppm for methane and from 0.315 to about 0.41 ppm for nitrous oxide. Radiative forcing would increase from 0.49 to 0.53 W / $m^2$ for methane and from 0.16 to 0.50 W / $m^2$ for nitrous oxide. Results of MAGICC computer model with methane and nitrous oxide emissions (natural plus anthropogenic) set at 535 and 13.6 Mt / y. T.M.L. Wigley, S.C.B. Raper, M. Salmon, and M. Hulme, ***MAGICC: Model for the Assessment of Greenhouse-gas Induced Climate Change*** (Norwich, UK: Climate Research Unit, University of East Anglia, April 1997).

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22.. The best estimates of 6.0 and 2.8 PgC/y in 2050 and 2100 represent the mean of seven carbon-cycle models for stabilization at 475 ppm early in the 22nd century. The uncertainty in the long-term forcing due to greenhouse gases other than carbon dioxide introduces an uncertainty (90-% confidence interval) of 1.1 and 0.6 PgC/y in emissions in 2050 and 2100. Differences between models produce uncertainties of 1.0 and 0.7 PgC/y; uncertainties in model parameters (fertilization and ocean update) produce uncertainties of 1.0 and 0.6 PgC/y in the Wigely model. Varying the rate at which stabilization is achieved introduces uncertainties of about 0.3 PgC/y. For stabilization at an equivalent doubling, I assume that biospheric emissions due to deforestation and climate feedbacks would be offset by absorption due to reforestation, with an uncertainty of ±1 PgC/y in 2050 and ±0.5 PgC/y. Emissions from cement manufacture are assumed to be 0.5 PgC/y in 2050 and 2100. The overall uncertainties of ±2 and ±1.2 PgC/y assume that the various errors are independent and combine randomly.

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# Proliferation Concern With Nuclear Power

W. G. Sutcliffe

## Introduction

It seems rather a daunting task to address any aspect of nuclear power for the next one hundred years, and proliferation and security concerns seem especially so. There are already wide differences of opinion (disputes) about the future of nuclear power in general, and the resulting potential for the proliferation of nuclear weapons in particular. However, having accepted the challenge laid out by the organizer of this session, Carl Walter, I will attempt to frame this topic (proliferation concern) in such a manner that the sources of disagreements, facts, projections, or values, can be identified and illuminated. In doing so I will briefly discuss threats, materials, fuel cycles, proliferation potentials, Article IV of the Non-Proliferation Treaty,[1] and some concluding thoughts. I will use the term "proliferation" below without a modifier, as is the case in current usage when referring to "proliferation of nuclear weapons."

## Threats

In dealing with the nuclear fuel cycle associated with electric power generation, it is essential to distinguish two threats. The first is the diversion* of nuclear material from the fuel cycle (safeguarded or not) to military weapons. This is a potential path of what might be called classical proliferation, acquisition by a nation of the capability to use nuclear weapons. We might broaden the concept of diversion to take into account the fact that although material might never have been diverted from electric power generation to military use, it is almost certain that expertise and infrastructure intended for the development of nuclear power have supported the development of a nation's (e.g., India) capability to use nuclear weapons. There is little that can be done to prevent the diffusion of technology and therefore its potential for misuse. The misuse of infrastructure is also problematic, but in large part can possibly be avoided by the application of safeguards. Additionally, we should note that the past is no guarantee that material will not be diverted in the future by a nation wanting to acquire nuclear weapons without delay.

It is important to recognize that there is no absolute supply side fix for proliferation, whether or not a nation has nuclear power plants. Any country with enough resources and time can obtain nuclear weapons. Supply side measures work to increase the difficulty, cost, time, visibility, and risk of proliferation. To prevent, or at least reduce the threat of proliferation, it is necessary to address the question of demand—regional stability, power, recognition, etc.

The risk of classical proliferation is probably greatest for the next few to several decades. After that time two factors will act to reduce the risk. First, there are increasing economic and

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* The usage of diversion here follows that explained by NAS[2] and paraphrased here: Although in many contexts the term "diversion" is used to mean any case in which an unauthorized party obtains a particular item, in the parlance generally employed in international non-proliferation efforts, particularly by the IAEA, a distinction is made between "diversion" and "theft." *Diversion* refers to removal of fissile material under safeguards by a legitimate owner nation (state) for military purposes, whereas *theft* refers to acquisition of these materials by other unauthorized parties.

cultural interdependencies of countries around the world. Technological progress in communications and transportation, as well as institutional measures such as free trade agreements and common currencies will continue to sustain and increase the importance of this factor. Because of these interdependencies there will be less incentive to use or threaten to use nuclear weapons, and hence less incentive to obtain them. Second, advances in technology will also drive the development of non-nuclear weapons, and it is likely that effective, more usable weapons will be developed, reducing the already small set of scenarios where nuclear weapons might be used or where such use might be a credible threat.

The second threat is that of theft of nuclear materials, overtly or covertly. It is likely that for the foreseeable future there will be groups, terrorists, who will want to cause, or threaten to cause, massive destruction and loss of life. A nuclear weapon or explosive provides a unique capability. One need only imagine what New York or Oklahoma City would have looked like had the World Trade Center or Murrah Building bombs been nuclear.

Nuclear or radioactive materials could also be used by terrorists to create radiological weapons. Although such weapons can be lethal, their primary effect is to make large areas unusable or uninhabitable. The size of an exclusion area and the consequent amount of disruption depends on the public's fear (terror) of radiation as well as the amount and method of dispersion of nuclear material. It is certainly possible that any such weapons will become less attractive as the public comes to a realistic understanding of the dangers of radiation, and possible protective measures. At this point, terrorists will realize that chemical or biological weapons are not only easier to obtain but possibly more effective as well.

## Materials

Now we turn to a consideration of the nuclear materials that are of concern. The material that gets most of the public attention is plutonium. There continues to be debate about the attractiveness and utility of reactor-grade plutonium for weapons. Too much of this debate on both the pro and anti nuclear technology sides seems to be an emphasis or de-emphasis of facts to support a position that either reactor-grade plutonium poses a great risk or very little risk for proliferation. Part of the problem is that all the known facts and details cannot be included in the arguments because of security considerations. More importantly, however, the attractiveness or utility depends greatly on the proliferation scenario assumed. Scenario, as the term is used here includes the capabilities and preparation of the proliferators. The difficulty is that for every scenario that emphasizes some factor there seems to be a scenario that de-emphasizes that factor or emphasizes some other factor. It's like the Abbott and Costello repartee: "Where did you get all those left-handed pitchers? The same place that you got all those left-handed batters." I hope we have at least gone past the point where the claim that reactor-grade plutonium cannot be used for weapons has any validity, and to the acceptance that essentially all plutonium must be made secure against theft and diversion.

The most troublesome aspect of using reactor-grade plutonium for weapons is the heat generated, primarily by the decay of Pu-238. The IAEA rule is that plutonium must consist of more than 80% Pu-238 before safeguards can be relaxed. Reactor-grade plutonium usually consists of 1 or 2% Pu-238. Plutonium used in weapons contains only about 0.02% Pu-238.

Uranium, highly enriched in U-235, is the other material of primary concern. Depending on the enrichment, HEU may be more attractive than plutonium for making weapons because simpler (gun-type) designs are possible. At present the use of HEU is not widespread and is limited to special purpose reactors. In spite of efforts to substitute high density LEU[3] in those special reactors, it is possible that HEU could find more use in the future. LEU, enriched to below 20% in U-235, is less of a concern but should still be safeguarded because it could be used as feed stock to produce HEU with considerably less effort and time than if starting with natural uranium.

If the thorium cycle is deployed, there will be concern about U-233. The bare-sphere critical mass of U-233 (16 kg) is considerably less than that for U-235 (48 kg) and is comparable to that for plutonium (11 or 17 kg for weapons-grade plutonium in the alpha or delta phase, respectively, and 13 kg for reactor-grade plutonium**). The IAEA (Information Circular No. 153) considers the sum of U-233 and U-235 in uranium for the purpose of safeguard issues. Although 20% enrichment is appropriate for U-235, it would appear that a somewhat lower value, 11.5%, would be appropriate for uranium enriched in U-233, as suggested by Minith and Vantine.[4]

Certainly other elements (e.g. neptunium, americium) could be used to sustain a chain reaction (nuclear power or nuclear weapons), but the prospects for their use appears unlikely at this time. However, if such elements are separated as part of the back end of the fuel cycle they should be protected against theft and diversion. There is no provision at present to safeguard these materials.

The form in which the material (plutonium or HEU) resides also determines its attractiveness, as it contributes to the ease, speed, and visibility of fabricating weapons. The hierarchy of common forms, from the most to least attractive, is metal, oxide, fresh MOX or HEU fuel, and irradiated MOX or HEU fuel. One could also include material in process. Compounds in solution, such as in the PUREX process, would fall before or after fresh fuel depending on whether one is considering a diversion or theft scenario. Material in process for an ALMR with fuel recycle or in a molten salt reactor would fall before or after irradiated fuel, again depending on the type of scenario.

Clearly, measures to protect materials from theft or diversion should be matched to the attractiveness of the materials. Unfortunately, attractiveness, in the broad sense used here, is not well defined and depends on the threat scenarios considered to be credible. Because the consequences of misuse can be enormous, conservative measures are employed. As technology, for detection, protection, etc., and institutional controls evolves over the next one hundred years it may be that protective measures can be more efficiently matched to attractiveness.

## Fuel Cycles

Fuel cycles are usually considered to be open or closed, and there seems to be considerable disagreement as to the relative potential for proliferation between the two. A very simple characterization of the more common fuel cycles, as shown in Fig. 1, will serve our purposes. The open or once-through cycle for the LWR starts with natural uranium that is enriched to produce separated LEU which is then fabricated into fresh fuel. The fresh fuel is irradiated in a reactor producing heat, power, and spent fuel. Heavy-water reactors, such as the CANDU type, can operate on natural uranium so that the enrichment process can be eliminated. The radioactive spent fuel is stored under water until it is cooled sufficiently for disposal. Thus far, no country has permanently disposed of any spent fuel. Currently, in the U.S. sentiment is building for interim (long-term) storage[5].

The MOX fuel cycle involves recycling but is not completely closed. In this fuel cycle separated uranium and plutonium are combined into fabricated fresh fuel. As in the case of the

** The isotopic compositions of weapons- and typical reactor-grade plutonium are 94% Pu-239, 5.8% Pu-240, 0.2% Pu-241; and 58% Pu-239, 27% Pu-240, 9% Pu-241, 6% Pu-242, respectively.

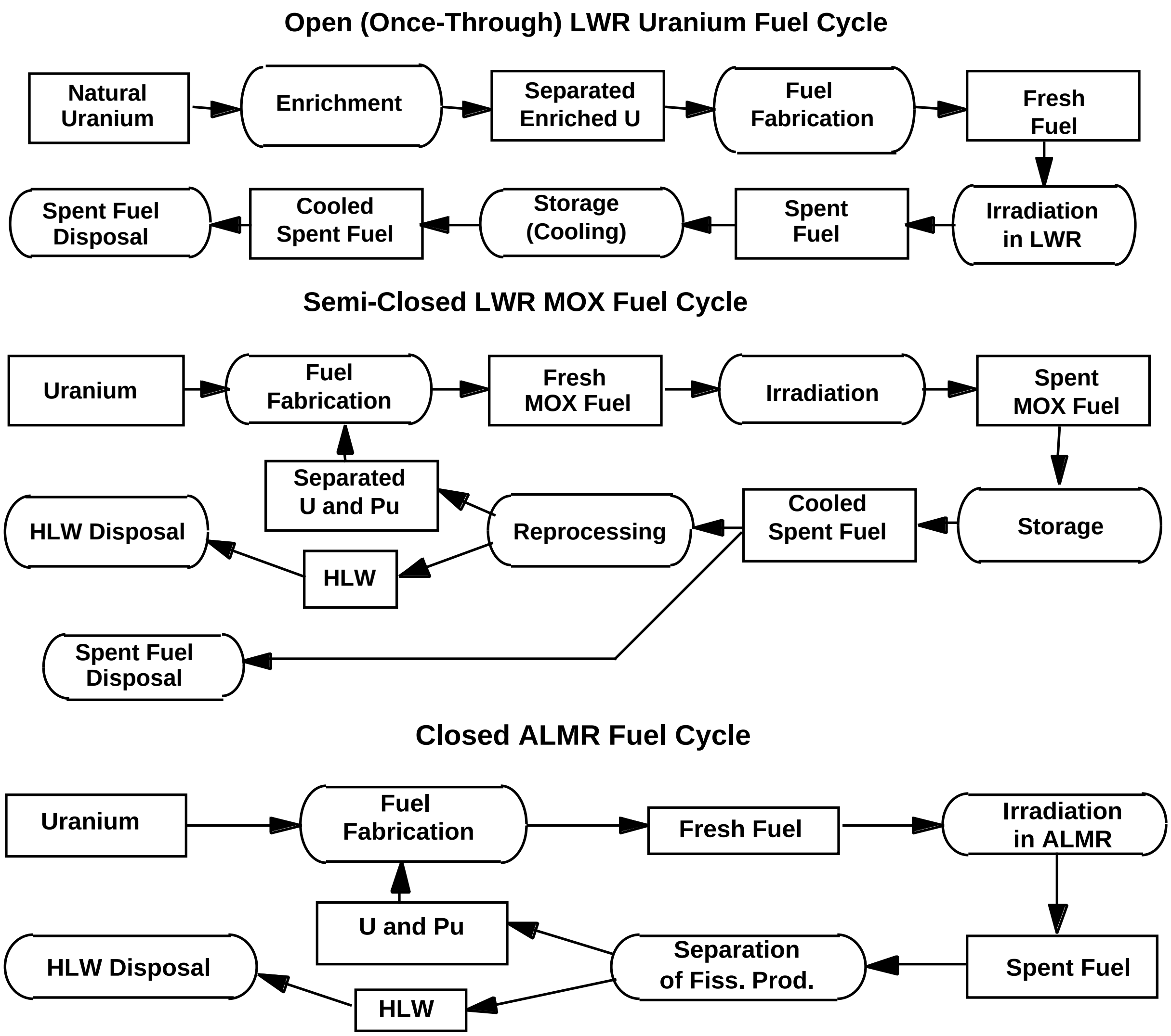


**Figure 1. Open and closed fuel cycles**

open cycle, the fresh fuel is irradiated in a reactor producing heat, power, and spent fuel. Rather, than disposing of the spent fuel after an appropriate cooling period, the closed cycle separates (recycles) the plutonium for fabrication into new fuel. Because of the isotopic changes (relative increase of heavier, less reactive isotopes) plutonium cannot be recycled in thermal reactors (LWRs) more than once or twice. In this case a significant fraction of the original plutonium must be disposed of. It is possible, during the next century that isotopic separation will be sufficiently advanced so that separation of Pu-239 could be economical. In this case Pu-239 could be recycled while the heavier plutonium isotopes could be burned in reactors with a fast neutron spectrum. A closed MOX fuel cycle is currently possible by utilizing LWRs in conjunction with fast reactors.

The fuel cycle employing fast reactors (ALMRs) differs from the above fuel cycles in a number of respects. Because of the fast spectrum, it is not necessary to dispose of plutonium or higher actinides. Because of the build up of heat-producing isotopes, the fuel is not suitable for weapons. Current ALMR concepts include on-site fuel recycling. Thus, recycled plutonium always resides in a protected radioactive environment. Another difference is that it is not necessary to dispose of the fission products with every cycle, and the waste product contains no actinides.

## Proliferation Potentials

This section might have been entitled Proliferation Resistance, but the focus here is more on vulnerabilities than on the means to strengthen security. It should be noted that gallant efforts have been made[6,7,8] toward quantifying proliferation risk. Whether, or to what extent, a fuel cycle is vulnerable to proliferation depends on whether we are concerned with theft or diversion. For example, items such as fresh MOX fuel assemblies, or even separated plutonium in sealed cans, are unlikely to be the target of diversion because of detection resulting from MC&A procedures. On the other hand, items such as these could be attractive targets for theft. Diversion of materials in process is less likely to be detected due to the inherent uncertainties in measurement and so are more attractive for diversion. Because of the difficulty of handling bulk materials, especially radioactive fluids, materials in process are not a particularly attractive target for theft.

Vulnerability depends on institutional (safeguards) and physical security measures, or the lack thereof, as well as the physical or chemical form of the target material. From the point of view of the latter alone, we can see why the once-through cycle appears to be less vulnerable to diversion, and the MOX fuel cycle appears more vulnerable to both theft and diversion. From this point of view, the ALMR fuel cycle has the advantage of not discharging spent fuel containing plutonium. Also, noting that all aspects of this fuel cycle are localized, it is less vulnerable to theft and diversion than the MOX fuel cycle.

In discussing diversion, it is important to note that for the next decade or so, nations that have nuclear weapons are unlikely to be motivated to divert material from power reactor fuel cycles for military purposes. For even with the present arms control agreements, or if a fissile material cutoff treaty were to be concluded, these nations will undoubtedly reserve enough (more than enough?) material for the needs of their stockpiles of nuclear weapons. It is hard to see how a breakout from arms control agreements to higher numbers of weapons would be advantageous. If these nations were to embark on this course (breakout), it would almost certainly produce plutonium rather than divert it from commercial power facilities. This is because the isotopic compositions of plutonium derived from power reactors are considerably different than that most suitable for weapons and results in significant design and fabrication implications.

Only when the nations with nuclear weapons have reduced their stockpiles to very low levels will diversion become a real threat. However, by this time, a few to several decades hence, the technology to measure bulk materials (in process) and to detect diversion may be so capable as to make any diversion readily apparent. This would not remove the threat but it at least would provide a warning, and thus act as a deterrent. In fact, such detection capability might be a necessary condition for reductions to low numbers of nuclear weapons.

## Proliferation and Article IV of the NPT

It appears that we are in a paradoxical situation. We are committed to the NPT, including Article IV, which grants “…the inalienable right of all the parties to the treaty to develop research, production and use of nuclear energy *[sic]* for peaceful purpose without discrimination … “ and “…the fullest possible exchange of equipment, materials, and scientific and technological information…" However, we do not trust a number of nations, e.g., Iraq, Iran, and DPRK, not to misuse nuclear facilities, equipment, and materials.

We may wish to interpret Article IV as a long-term ultimate goal, but to many nations it is an achievable near-term requirement. This leads to a number of questions. Should there be conditions, in addition to promised compliance with the NPT, to be met before receiving (or developing) nuclear technology? Such conditions might include transparency and *impeccable nonproliferation credentials* (whatever that might mean). Most nations are calling for global non-discriminatory regimes, e.g., CTBT and FMCT, so any explicit discrimination faces difficulties, and would have to be based on internationally accepted criteria. Although the IAEA program of strengthened safeguards (known as: 93+2) involves more transparency and makes undetected proliferation less likely, we are still faced with a daunting problem. What measures can the UN or the U.S. take in response to withdrawal from, or violation of, the NPT? Cases to consider, for example, are DPRK and Iraq.

No easy solution to this paradox is apparent. However, some measures may begin to address the problem. Regional compacts with transparency (declared stocks of fissile materials in all phases of the nuclear fuel cycle), and enhanced safeguards could provide the basis for more constructive cooperation under Article IV. Internationally controlled (owned, operated) fuel cycle facilities, including spent fuel storage (IMRSS),[9] reprocessing and fuel fabrication facilities, might be possible.

## Conclusion

It seems to me that the two major forces that will drive the issues surrounding nuclear power and proliferation of nuclear weapons in the next century are population growth and progress in science and technology. Because of widespread communications, population growth will translate into an irresistible demand for a better (more uniform) standard of living globally, and thus a demand for more energy, specifically electric energy. A significant portion of this new energy, if not most, will undoubtedly be supplied by nuclear power plants. Two other, less certain, factors, depletion of energy resources, and concern for the environment, will certainly influence the portion of new energy generating capacity that will be supplied by nuclear power plants.

As nuclear power continues and grows there will continue to be concerns about proliferation. However, as mentioned earlier, as technology develops and is more widely deployed, particularly in the communications and transportation areas, the interdependencies among nations will reduce the demand for nuclear weapons and hence lower the risk of diversion. Unfortunately, the threat of terrorism will likely continue and so will the risk of theft of nuclear materials. This threat, may however be blunted somewhat by improved protective measures and advances in sensor technology.

We are seeing astonishing advances in technology, particularly in communications and computations areas. Because of the size, complexity, and infrastructure requirement, I think we are unlikely to see the same dramatic advances in means for the production of energy. Nevertheless, it is possible that by the end of the next century fusion power plants will be developed and the reliance of fissile materials will diminish. Even in this case, however, materials, including buried spent fuel (if any) will have to be protected.

Finally, I think that all proliferation concerns can be addressed and should not inhibit an enduring nuclear fuel cycle.

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# Fast Reactor Fuel Cycle

**Marion L. Thompson**

## Introduction

The fast reactor fuel cycle is an integral part of the Fast Reactor (recycle) System. In contrast, the traditional LWR fuel cycle, at least currently in the U.S., is a once-through cycle wherein, low-enriched $UO_2$ is fabricated, irradiated in dispersed LWRs and disposed of as (spent fuel) waste. Development work was performed in the U.S. and other countries to recycle plutonium to LWRs. Some countries (e.g., France, UK, and Japan) plan to or currently recycle plutonium via processing the spent fuel to recover the plutonium for fabrication as MOX fuel for return to LWRs. Due to the “poisoning” effects of producing additional higher isotopes of plutonium and other actinides, LWRs are limited to only a few cycles of plutonium recycle.

The fast reactor can recycle plutonium essentially indefinitely with periodic removal of fission products and addition of depleted uranium[1]. The higher isotopes of plutonium and the other actinides reach an equilibrium value in the fast reactor and do not “poison” the fast reactor core.

The traditional fast reactor fuel cycle for most world-wide applications is based on the blending of MOX fuel from $PuO_2$ and $UO_2$ feed. A variation on this approach, is co-precipitation of Pu and U from a (nitrate) solution. This is an effective way to attain maximum fuel homogeneity and powder activity for sinterability. However, homogeneity of blended MOX exceeds requirements by about an order of magnitude. Also, liquid processing creates liquid (TRU) waste to be processed, limits process streams by criticality concerns, and is generally not perceived to be as amenable to MOX production as blending $PuO_2$ and $UO_2$.

Processing either LWR or fast reactor spent fuel is not currently practiced in the U.S. as it is in some countries. Based on concerns about proliferation of countries having nuclear weapons and materials, diversion, particularly for aqueous processing of spent fuel, President Carter halted “reprocessing” in the U.S. The aqueous process was originally developed for recovery of weapon plutonium and is therefore capable of producing very pure plutonium. Of course, the aqueous process can be operated as a “dirty” process, wherein some fission products, actinides and uranium could be processed with the plutonium to reduce attractiveness for weapons. Notwithstanding this approach, material diversion and weapon proliferation remain concerns and although the Carter order was rescinded by President Reagan, “reprocessing” is currently “politically incorrect” in the U.S.

An alternative, fast reactor fuel cycle developed by Argonne National Laboratory, is based on metal fuel processed via a pyrochemical (dry) method. This process is considered to be far more theft / diversion resistant than aqueous processing.[2] Note: This is not to say that the aqueous process cannot be safeguarded—worldwide safeguarding is currently being achieved. However, the pyrochemical process produces a plutonium product mixed with fission products, actinides, and uranium that is not useable for weapons without recycle / purification in an aqueous process (an additional significant process activity). The metal fuel cycle should be very attractive for future deployment of fast reactors.

The development of fast reactors has been on-going for several decades but it is still perceived by policy makers that they are not needed at this time to better utilize our limited uranium resources by using most of the uranium instead of only ~0.5% in LWRs.

## Electrical Energy Demand Projection

EPRI conducted a study in 1995, to evaluate plutonium in spent fuel and its economic potential over the first half of the next century.[3] It was recognized that there are other considerations that might influence the results but this study was conducted as an economic study. The study considered several aspects of the issue, such as world population growth, electrical energy demand, electrical energy supply from other sources, time to develop future fast reactors and attendant fuel cycles, uranium supply, and uranium consumption/commitment for LWRs. The EPRI study considered the time period to about the middle of the next century. Figures 1 through 7 were extrapolated from the EPRI data to the year 2100 in an attempt to provide projections for a somewhat longer time period.

The basic conclusion of the EPRI study is that the use of plutonium in fast reactors is likely to be economically competitive with uranium in LWRs and justify deployment by about 2035. Development and licensing of the fast reactor needs to precede this date, probably by about three decades. Obviously, the fast reactor deployment date cannot be established precisely and may occur earlier or later than projected. However, more importantly, considering the apparent finite supply of fossil fuel and uranium and unless a currently unknown energy source is rapidly developed, fast reactors will be needed in large numbers within a few decades to supply growing electrical energy demand, moderate the cost of uranium (for LWRs), and provide waste processing and other benefits to the world population.[4,5]

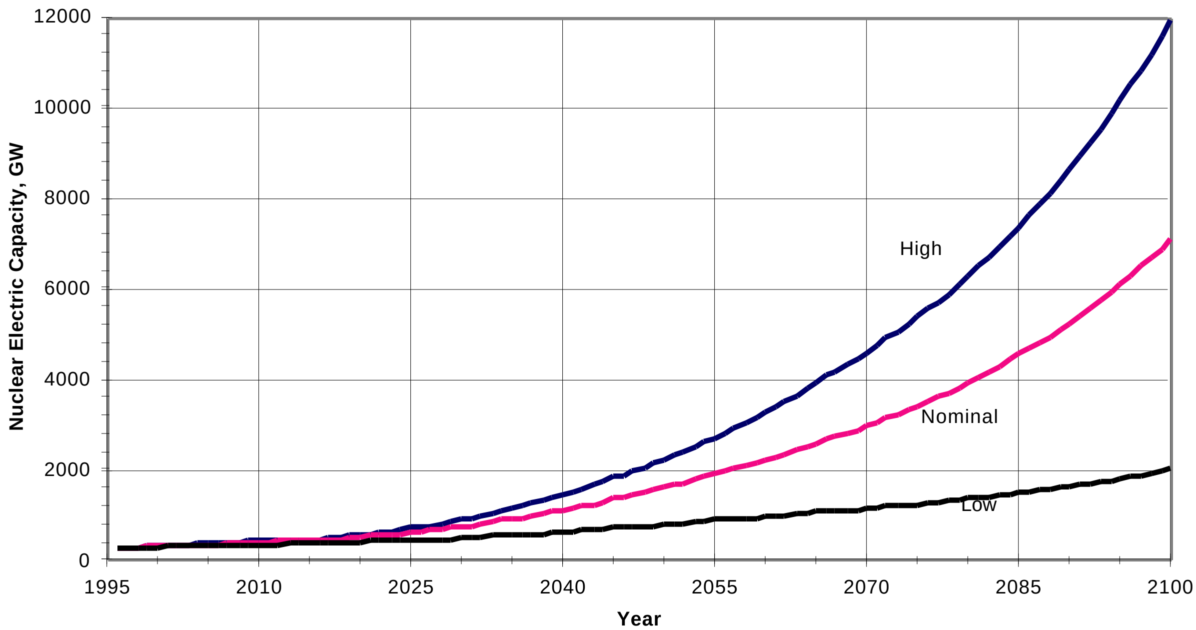


**Figure 1. Global nuclear power capacity growth forecasts**

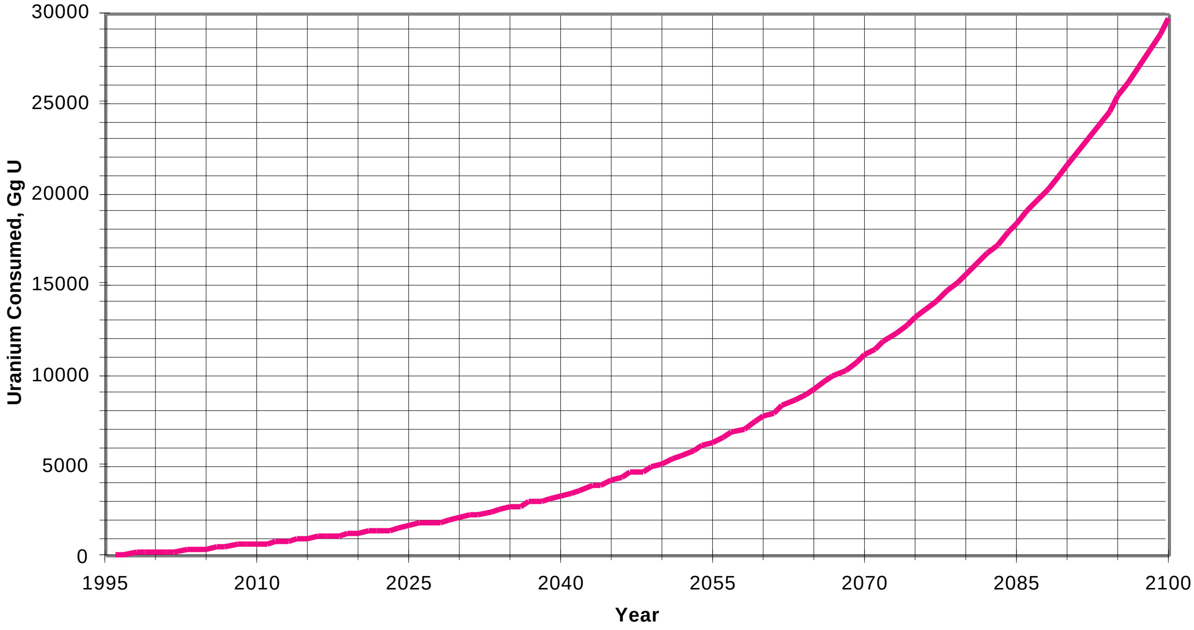


**Figure 2. Nominal projection of uranium consumed**

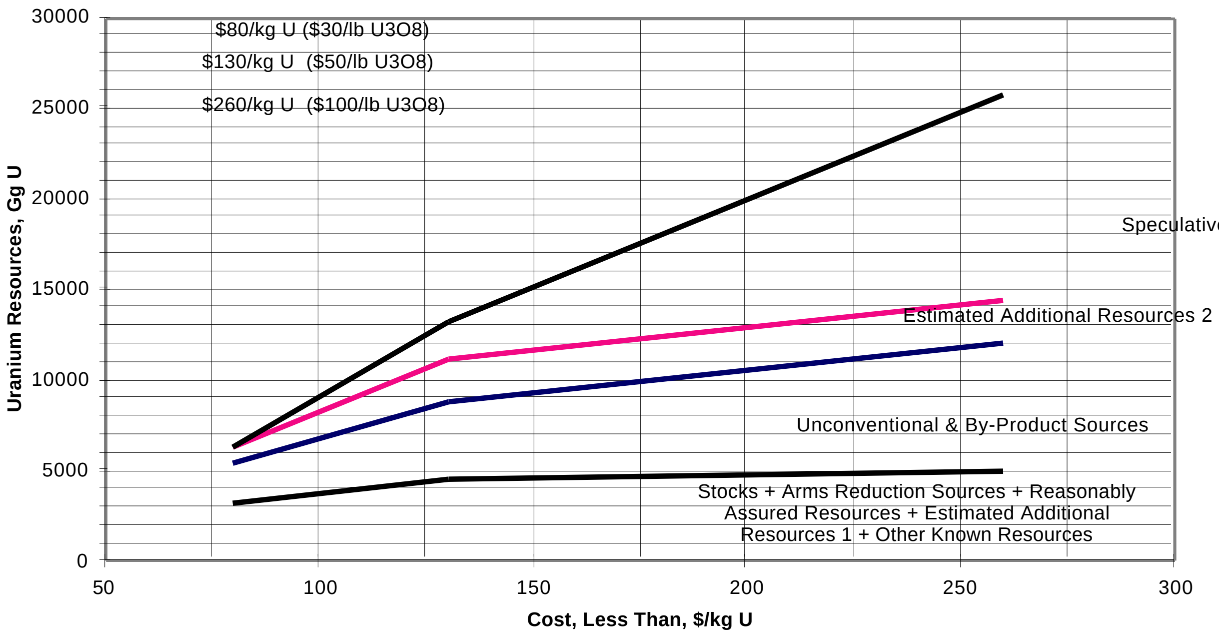


**Figure 3. Forecast uranium resources vs. cost**

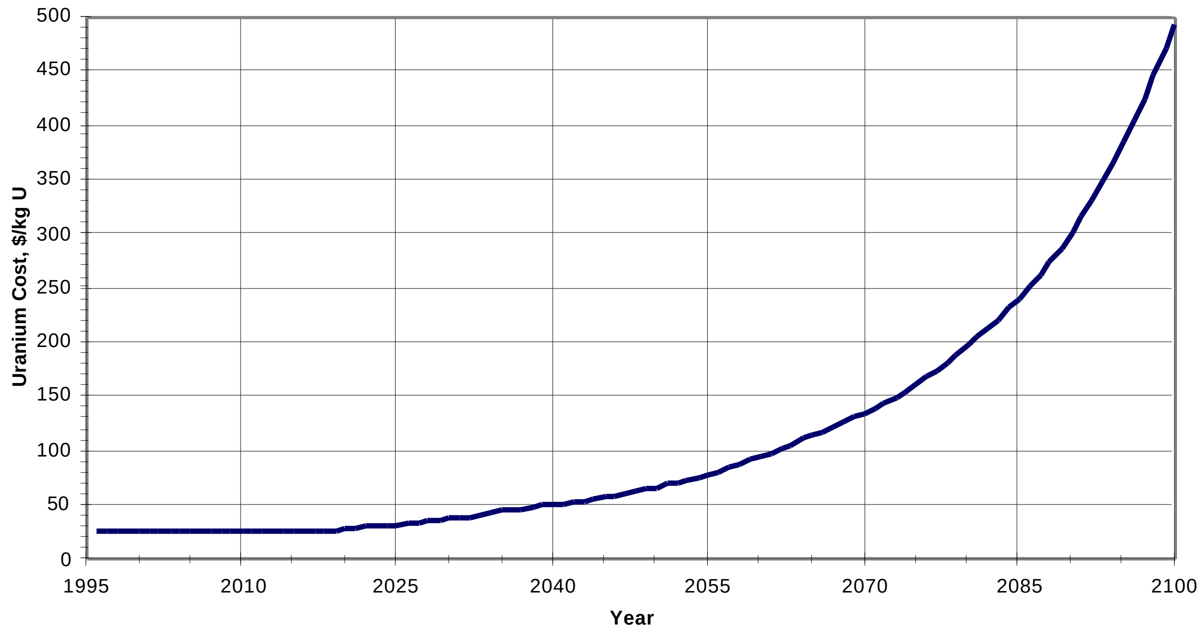


**Figure 4. Nominal projection of uranium cost vs. time**

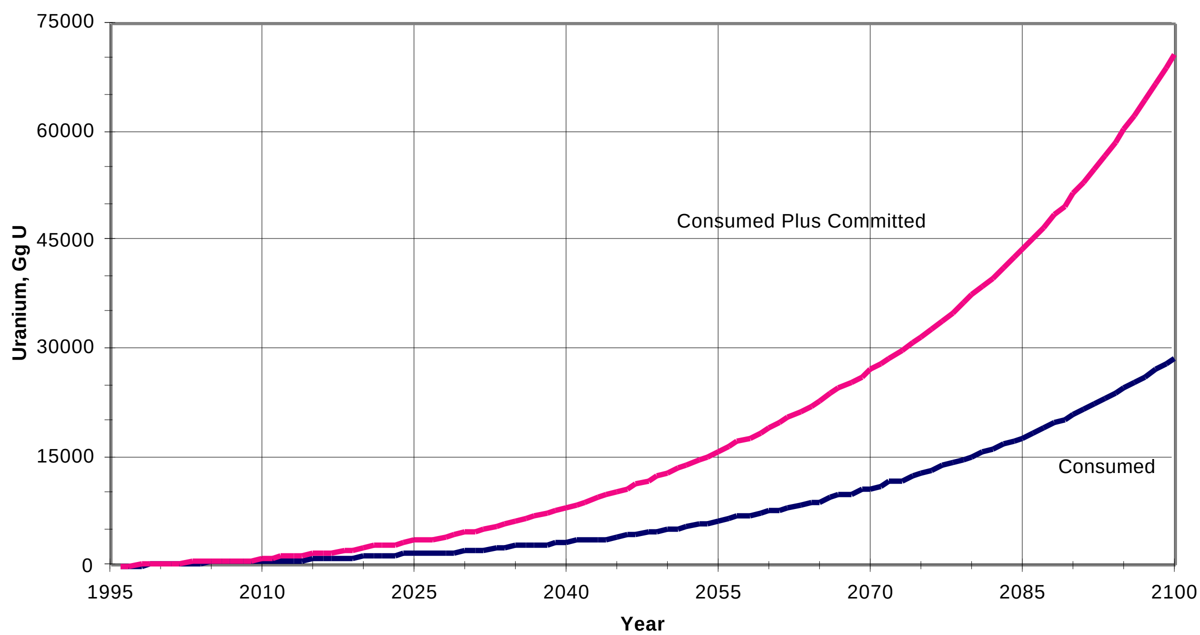


**Figure 5. Nominal projections of uranium consumed and committed**

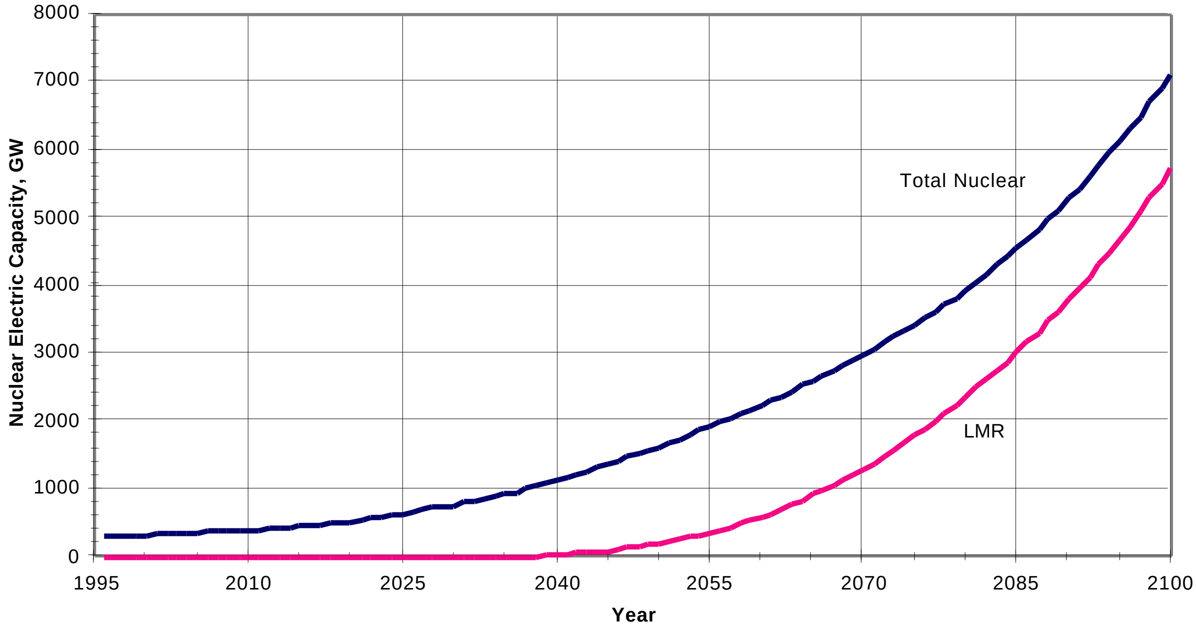


**Figure 6. Illustrative projection of LMR capacity growth**

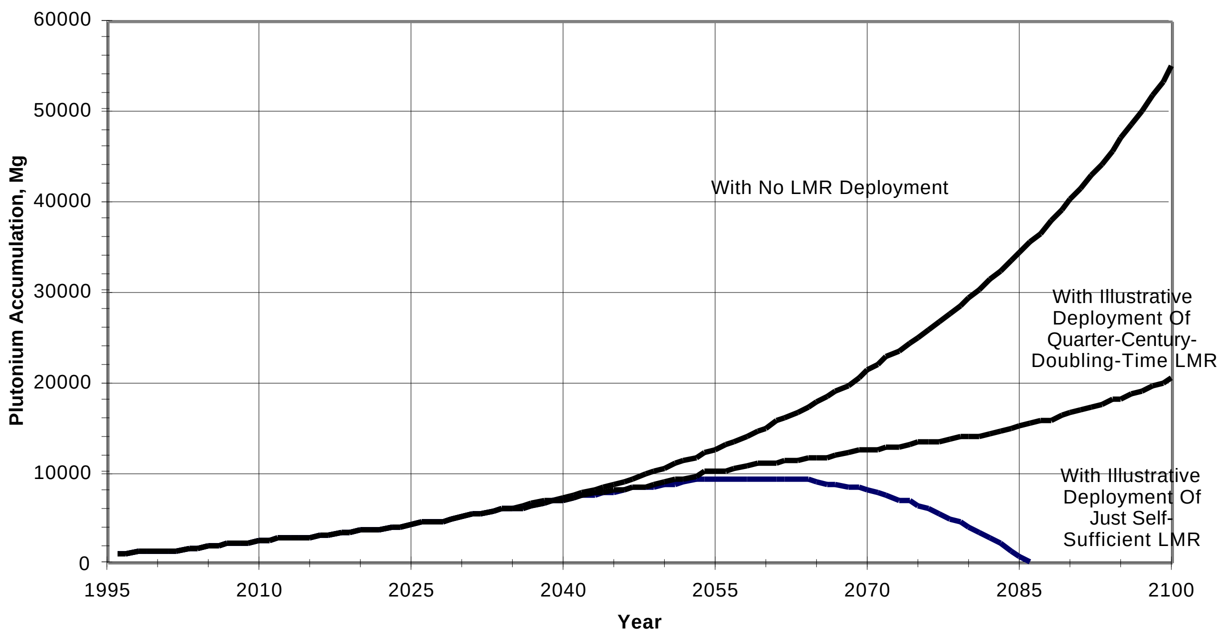


**Figure 7. Nominal projections of plutonium accumulation in LWR spent fuel**

## The Fast Reactor Solution

The best (and currently only) technology capable of meeting the impending electrical energy demand is the fast reactor system. ALMR is an attractive fast reactor that was being developed in recent years by a team led by General Electric Company under contract to DOE. This contract has expired but development of a larger, simpler, more cost-competitive ALMR (Super PRISM) continues with interest and support from the Pacific Rim. The ALMR is a sodium-cooled, pool-type, modular, passively safe, cost-competitive reactor. The basic philosophy for deployment of the ALMR is to co-locate the fast reactor and the fuel cycle facility. In addition to the theft/diversion resistance of the reference metal fuel cycle, co-location precludes the need for shipment of plutonium between the fuel cycle facility and the reactors. This should enhance theft/diversion resistance of the Fast Reactor/Fuel Cycle system. The current cost projection for power from this ALMR design is <3.5 cents/kWh.

## Benefits of the Fast Reactor (Recycle) System

The extensive benefits of the Fast Reactor System, particularly the ALMR design, are listed below:[6,7]

1. The ALMR modular design with no internal moving parts is fundamentally very sound. This approach accommodates licensing by the ability to test a full- size prototype reactor at a lower cost.
2. The ALMR passively safe operating/shutdown features assure that safety is not maintained primarily by "engineered" components/methods/procedures requiring man interface. The reactor is "walk away" safe for all upset conditions.
3. The ALMR design shown in Figure 8 is a close-coupled reactor/steam generator/heat exchanger system mounted on seismic isolators to preclude significant relative motion of components during seismic events. Natural phenomena potentials are mitigated in the design.
4. A constantly operating passive air cooling system provides safe shutdown for the ALMR during all loss-of-coolant events.
5. If desired, or when no longer needed, the fast reactor can burn or destroy all available actinides, including plutonium, down to one final small reactor core with a "burner" core.
6. The fast reactor conversion ratio can be readily controlled to regulate the inventory of plutonium. Again, this is an important item relative to proliferation/diversion resistance and other related issues.
7. The fast reactor is non-polluting and emits no greenhouse or acid rain gases. It provides a significant (and perhaps the only) opportunity to reduce long-term emissions.
8. The fast reactor preserves valuable natural resources such as oil, gas, and uranium and can provide electrical energy, economically for centuries using previously mined uranium.
9. The fast reactor is capable of transmuting undesirable fission products to preclude long-lived hazardous waste products. Fission products needed for medical isotopes and other applications can be separated in the fuel cycle.
10. Recycle of plutonium in the fast reactor precludes plutonium and other actinides in the waste repository. This precludes a "plutonium mine" legacy for future generations and also precludes very long-term safeguards/surveillance/cost.
11. Fast reactor liquid metal coolant supports higher thermal efficiency.

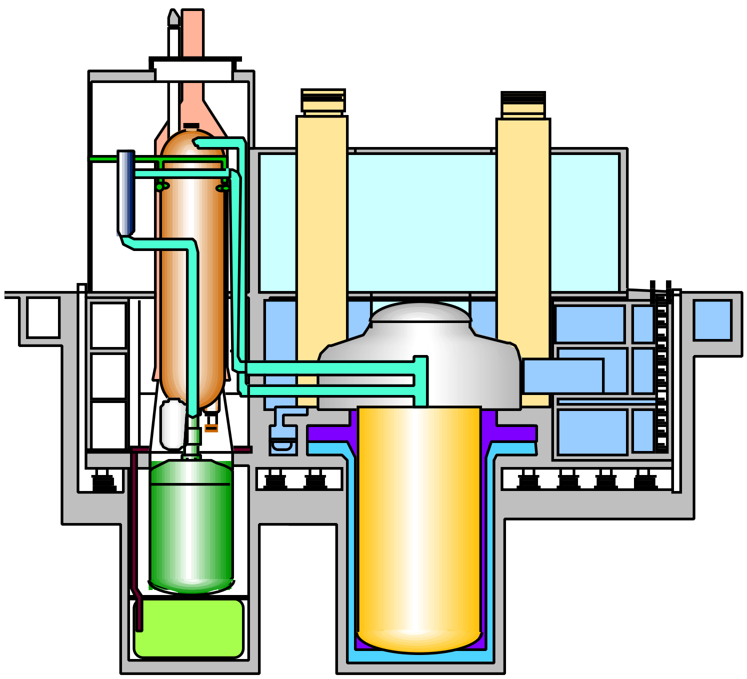

**Figure 8. View of the modular ALMR and steam generator**

12. The fast reactor requires only the addition of U-238 as resource fuel. Depleted uranium is therefore converted from a liability to an asset (with huge energy content).
13. Fast reactor fuel cycle waste is free of actinides and contains only fission products. This results in significantly less heat load in the repository and a waste that is far less toxic than spent fuel. The waste toxicity is reduced to the level of natural uranium in about 300 years compared to millions of years for spent fuel. Repository surveillance requirements should be greatly reduced. At least four times the amount of equivalent energy production waste (free of actinides) can be placed in the repository, reducing the cost of waste disposal.

## Conclusions

Ethical attention to the consequences of our actions upon future generations dictates that they must not result in:

1) A legacy of "plutonium mines."
2) Long-lived hazardous waste with very long safeguards/security requirements.
3) A polluted environment resulting from burning fossil fuel.
4) Depleted gas and oil based resources.
5) Stored, unused, depleted uranium with vast energy content.
6) High toxicity stored waste.
7) Inefficient waste disposal due to contained heat load
8) Loss of nuclear energy technology lead to other countries and the need to buy it back (at higher cost) when needed.
9) Widespread poverty due to lack of electrical energy ("we've got ours, let them get theirs" approach).

The fast reactor provides opportunity for extensive long-term electrical energy generation while meeting the above ethical issues and benefits.

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# Back End of an Enduring Nuclear Fuel Cycle

K. K. S. Pillay


## Abstract

An enduring nuclear fuel cycle is an essential part of sustainable energy consumption, the process whereby the world's riches, our resources, are consumed in a responsible manner so that future generations can continue to enjoy at least some of those resources. In many countries the goal of sustainable development has focused attention on the benefits of nuclear technologies. However, maintenance of the nuclear fuel cycle is dependent on sensible management of all the resources of the fuel cycle, including energy, spent fuel, and all side streams. The nuclear fuel cycle for energy production has suffered many traumas since the mid-1970s. The common basis of technologies for nuclear explosives and nuclear energy has been a preoccupation for some, a predicament for others, and a perception problem for many. This paper identifies some pragmatic steps necessary to reverse the present trend in the U.S. and to maintain a necessary fuel cycle option for the future.


## Introduction

Management of the back end of an enduring fuel cycle is not waste disposal. It is the responsible management of all the resources from residues of nuclear power generation so that the benefits of a nuclear fuel cycle will endure. Nuclear fuel cycles that evolved over the past five decades allow the international community to consider numerous ways for integrating nuclear material processes and reactor technologies to serve mankind. All techniques available for the disposal of radioactive waste and utilization of spent fuel resources are fully compatible with sustainable development. However, the decision of a few nations to declare and discard spent fuel as waste is not compatible with sustainable development and does not contribute to the goals of an enduring nuclear fuel cycle.

In 1989, the IAEA submitted a report to the UN on the practical contributions of nuclear energy to "Sustainable Development." In 1992, recognizing the rapid depletion of natural resources and the resulting major environmental impact, the Royal Academy of Science, London, and the U.S. National Academy of Sciences issued a joint statement called "Sustainable World." The concept of sustainable development was the main theme of the 1992 UN Conference on Environment and Development in Rio de Janeiro. In 1993, at the Conference of World Science Academies in New Delhi, 58 countries expressed concerns over the rapid population increase and future resource requirements. As a result of all these concerns, many nations and several international organizations, including the UN, have been embracing "sustainable consumption," the process whereby natural resources are consumed in a responsible manner that respects the needs of future generations. In June 1997, Hans Blix, the Director General of the IAEA, reported to the Special Session of the UN on Sustainable Development that in many countries the goal of sustainable development has focused attention on the benefits of nuclear technologies.

Contrary to the goals of sustainable development, we have been consuming energy resources as though we are the last generation on this planet. Governments of a few nations attribute their disaffection with the concept of an enduring nuclear fuel cycle to "public concern" over nuclear waste and the potential proliferation of weapons. However, the realists of the world recognize that fuel resources are finite and all known fossil fuels (except coal) will be depleted well within a century, if not earlier. The energy needs of future generations will be met by other sources, including the vast energy resources of the so-called waste spent fuel repositories.

## Context

When the Cold War ended, the attention of the world community suddenly turned toward the ideal world of disarmament and elimination of nuclear weapons. Although this is a highly desirable goal, there are those who consider nuclear disarmament a fool's errand. Because the national security of several nations is still dependent on nuclear weapons, it is unrealistic to expect a sudden elimination of all nuclear weapons. Even a systematic dismantlement of all existing nuclear weapons would take many decades. Unfortunately, this highly desirable goal of nuclear weapon elimination has also allowed a vilification of nuclear technologies by opportunists and a move to banish all separated fissile materials from the biosphere. These developments are detrimental to the survival of an enduring fuel cycle that is essential for the survival of future generations.

Although the contributions of science, in general, are recognized as essential for a better future, the ability to creatively channel nuclear technologies has to overcome numerous ethical travesties. Unfortunately, the mass media often associate nuclear technologies with weapons of mass destruction. In a recent editorial in *Science Magazine*, President Clinton stated that "…science has no soul of its own. It is up to each of us to determine whether it will be used as a force for good or evil. We must decide together how to apply ethical and moral principles to the dazzling new discoveries of science."

Some of the lingering issues of nuclear technologies include: illogical fear of radiation and genetic mutations, perceptions of imminent danger to human beings from radioactive waste, and a paranoid fear of nuclear weapon proliferation. Fear of radiation has proved to be much more detrimental to public health than radiation itself. There is a pervasive fear of radiation of all types among the public. Thousands of people avoid lifesaving medical procedures, such as mammograms and radiotherapy, because they involve radiation. Portrayal of radiation-induced mutations and nuclear material theft by the mass media and the entertainment industry may be causing some of the irrational responses by the general public. After the Chernobyl reactor accident in 1986, it is reported that over 100,000 additional abortions took place in that part of Central Europe because of the fear of mutants being born as a result of radiation exposure.

Although the legacy of radioactive waste generated from defense production is not something to be proud of, it should be recognized that all the radioactive waste in the U.S. is located far from population centers and has not created any undue hazard to human health. However, a popular perception is that there is imminent danger to human beings from radioactive waste. Similarly, the potential diversion of fissile materials for clandestine nuclear weapons has been exploited to discredit all uses of nuclear technologies, leading to a mentality of "…choke the system until all nuclear weapons are eliminated from this planet."

## Evolution

Since 1946, when the Baruch Plan for the international control of all phases of the development and use of atomic energy was proposed, there have been various diversions to using the full benefits of nuclear energy. The origins of the U.S. nuclear power policy are generally traced to President Eisenhower's famous Atoms-for-Peace speech at the United Nations in 1953. The next two decades saw reasonable progress in the peaceful applications of nuclear energy. However, a series of international events affecting energy supplies led to a major global Nuclear Power Conference in Salzburg in 1977. In particular, this conference addressed the problems of nuclear fuel cycle and the need for its integration at both the national and international level.[1] The mid-1970s also saw major changes in U.S. policies toward nuclear energy and the saga continues even today.

In 1977, against the background of mounting energy demands and the realization that fossil fuel resources are finite, the INFCE committee was formed in Washington, DC and requested the participation of 31 countries and four international agencies. INFCE examined all possible options for nuclear energy use and assessed the interrelated problems associated with peaceful uses of nuclear energy and the risk they may pose of weapon proliferation.[2] This detailed examination of the nuclear fuel cycle was conducted under the auspices of IAEA and the final report was released in 1980. Although this objective examination made many valuable recommendations, the divergence of interests among nations resulted in different nations adopting different strategies for the use of nuclear energy. Again during the 1995 discussions regarding the extension of the NPT, the subject of nuclear energy was discussed in the UN's forums to enlarge the continued use of nuclear technologies worldwide. These attempts have yet to produce a satisfactory global strategy for maintaining the use of nuclear energy and an enduring nuclear fuel cycle.

Although nuclear technologies have benefited mankind in numerous ways, the lack of public acceptance has adversely affected progress toward an enduring nuclear fuel cycle. The widely accepted applications of nuclear technologies are in areas of medical and health care needs, followed by a multitude of applications in food, water, and agricultural needs. Public concern about radioactive waste management and weapon proliferation has overshadowed the great benefits of all nuclear technologies.

It is generally recognized that one of the reasons for the public perception of nuclear technologies is the past neglect of the back end of the fuel cycle. In the early days of nuclear technology development it was not fashionable to work on the "garbage problem" because of the opportunities to indulge in numerous esoteric applications of evolving nuclear technologies. It was simply assumed that waste streams can and will be managed with ease. This assumption had serious limitations and it took nearly three decades before our perceptions changed, along with all other environmental concerns, that resulted in landmark legislations in the U.S. Large resource commitments in recent years to waste management and environmental remediation is clear evidence of the changes in our priorities. Although this is a welcome change, the focus on waste management and environmental remediation may have contributed to the neglect of an enduring fuel cycle that promises reliable energy resources for many millenniums.

## The Need

At the end of 1995, 69 nations reported "significant nuclear activities," but only 32 of them had nuclear power programs of significance.[3] The world is consuming energy resources at a dramatically increasing rate. Demographers estimate the world population will double in 50 years, and WEC has estimated our energy needs will double in 20 years.[4] It is generally recognized that nuclear energy is an essential contribution to future energy needs and that reliable energy sources for a modern society can be provided by nuclear power plants. However, there have been considerable obstacles to developing a worldwide common strategy for the use of nuclear energy.

The 1972 UN Conference on Human Environment held in Stockholm, and the 1992 "Earth Summit" held in Rio de Janeiro were focal points of issues related to environmental problems associated with burning of fossil fuels. The U.S. joined the United Nations Framework

Convention on Climate Change in 1996 and agreed to stabilize $CO_2$ and GHG emissions at 1990 levels by the year 2000. There have been many intellectual discussions and an in-depth examination of the issues and opportunities surrounding this goal.[5] Realizing the difficulties of reducing GHG emissions, President Clinton recently announced new targets for GHG reductions in the U.S., changing the target date to between 2008-2012.[6] According to the U.S. Energy Information Administration, the projected 55% increase in energy demand during the period 1995–2015 will increase GHG emissions by 54% if these energy resources are fossil fuels.[7] During the same period, the U.S. will retire 40% of its nuclear power generating capacity. As a consequence, the demand for electrical energy generated from fossil fuel will raise annual $CO_2$ emissions by 90 TgC.

It is estimated that since 1958, the use of nuclear energy worldwide has reduced carbon dioxide emissions by about 8000 TgC. In 1995 alone, nuclear energy avoided the production of more than 600 TgC that would have resulted from coal-fired generation of electricity. Nuclear energy has already reduced global carbon dioxide emissions by about 7% and can make an even more significant contribution in the future. There is a growing demand for energy in the developing countries, particularly in Asia. To meet these demands without increased fossil fuel burning, several Asian countries are likely to increase their use of nuclear energy.[8]

Although there is skepticism about the influence of GHGs on global warning, there is increasing evidence of discernible human influence on global climate.[9] To meet the combined goals of energy requirements and environmental compliance, the industrialized nations of the world will have to depend more on electrical energy generated from alternative sources. Although nuclear energy will not be the only means of reducing GHGs, it will be an indispensable part of a thoughtfully conceived solution.

## Current Dilemma

Current plans by the U.S., Canada, and Sweden to discard spent fuel as waste ignore the sustainable use of nuclear technologies and a lack of concern for the resource requirements of future generations. The policies to discard spent fuel containing large quantities of fissile and fertile materials in geologic formations will create large concentrations of plutonium and uranium at few locations. As the radioactivity of the spent fuel decreases with time, the repositories will become attractive sources of plutonium, uranium, and a host of other strategically important materials.[10] Future generations looking for new energy resources will recover and reuse these resources, irrespective of the degree of difficulty created in the design of these repositories. Technologies for the safe recovery and reuse of the spent fuel resources for future energy production will be among the challenges for nations planning geologic disposal.

Governments of a few nations attribute their disaffection with the concept of a closed nuclear fuel cycle to public concern over nuclear waste and the potential proliferation of weapons. In addition, the electric utilities use near-term market conditions to justify their resistance to investing in a viable nuclear fuel cycle. These arguments have elements of credibility; however, the general public should also be aware of the following:

- The growth of antinuclear lobbying organizations as tax-free institutions and expansion of their information dissemination efforts into business ventures.
- Prevalence of “political correctness” in our culture and lack of an organized effort to counter organized, one-sided, information campaigns.
- The unwillingness of the private sector to invest necessary funds that will sustain a nuclear energy option.

## Ethical Issues

Transferring the burden of managing the discards of this generation to future generations is an issue of great significance in the overall process of managing nuclear energy resources. Those who favor the once-through fuel cycle are requiring that protection and safeguarding of spent fuel be continued for an indefinite time, even after placement in geologic repositories. The policies of the U.S. and the IAEA require that safeguards in geologic repositories of spent fuels be maintained for an indefinite future.[11] This assignment of a burden on future generations is contrary to all past human experiences and will continue to be a problem for the future. An alternative to this burden is retrievable storage of spent fuel as a future energy resource and making provisions for its protection and safeguards in the interim.

Radioactive waste management especially from worldwide weapon material production, has a history of poor performance. This negative image is often confused with the back end of the nuclear power fuel cycle, which is the management of all the resources from nuclear energy production. The Radioactive Waste Management Committee of the Nuclear Energy Agency of the OECD recently attempted to discuss the ethical dimensions of geologic disposal.[12] Although their report is intended to address only nuclear power generation, it carefully avoids mentioning “spent nuclear fuel” in the context of geologic disposal and instead substitutes the phrase “long-lived radioactive waste.” This politically correct discussion of the ethical dilemma of transferring waste management responsibilities misses the value of an enduring nuclear fuel cycle to future generations.

Those who embrace “sustainable consumption” should seriously consider the genuine needs of future generations and recognize the limitations of present generation(s). It is quite clear that the generation(s) responsible for creating plutonium in such abundance may not be objective enough to choose the most appropriate means of managing this material for the benefit of mankind. Therefore, it is more appropriate for the present generation to safely store this valuable material and let future generations, who will inherit the real costs of dealing with this material as a national debt decide on a disposition option.

## A Potential Solution

Discarding spent fuel as waste will result in large accumulations of fissile and fertile materials in several locations. Future generations will need to recover and use the resources in these spent fuel repositories as other energy sources are depleted. Therefore, it would be prudent to redesign the present once-through fuel cycle to accommodate future peaceful uses of spent fuel resources. This approach would require the following actions:

1. Design spent fuel repositories for future recovery of all spent fuel resources.
2. Develop a long-term investment strategy that considers the energy value of all fissile and fertile materials from spent fuels and maintain adequate safeguards on spent fuel repositories.
3. Develop technologies to improve all aspects of the nuclear fuel cycle and minimize the impact of the fuel cycle on the environment.
4. Remove legal impediments to expanding the use of nuclear technologies through private investments and convince electrical utilities to invest a percentage of their earnings to develop and maintain a viable nuclear fuel cycle.
5. Improve the safety and efficiency of uranium fuel cycles and develop the use of the world’s thorium resources as another fissionable material for energy production.
6. Manage legacy wastes from weapon material production and gain the confidence of the general public.

7. Support objective educational campaigns, based on fact, to change current public perceptions of nuclear energy.

In order to maximize the use of fissile and fertile materials and revitalize the back end of the fuel cycle in the U.S., it is necessary to build several MRS facilities for spent fuel in the near term. Because of current divisiveness about nuclear energy in the U.S., it may be prudent to postpone decisions on reprocessing and recycling of spent fuel for another hundred years when a new generation of consumers can make appropriate choices. After a hundred more years of radioactive decay, reprocessing spent fuels will be relatively simple. Also, it would be logical to have a reprocessing and fuel fabrication facility near each of the MRS facilities to maximize efficiency of the recycle system. The geologic disposal facilities may be used primarily for the disposal of vitrified waste from fuel processing. Such a strategy would address the safety and security concerns of this generation and meet the resource requirements of many future generations.

## Conclusion

Recycling of fissile and fertile materials in a closed fuel cycle will inevitably contribute to sustainable consumption. The use of plutonium in existing and new fuel cycles will increase as fossil fuel resources are depleted and alternative fuels are unable to satisfy the growing energy demand. Increasing concerns over global warning and the need to reduce greenhouse gas emissions can be addressed by including nuclear energy as an option for large-scale energy generation. The ethical predicament of generating energy from nuclear materials can be addressed by preserving the valuable resources of spent fuel for future use. International concerns over proliferation potentials can be addressed by maintaining minimum inventories of separated fissile materials and through continued consumption of separated fissile materials in an enduring nuclear fuel cycle. It is essential to reestablish an innovative management strategy for the back end of the nuclear fuel cycle that can sustain the resource requirements of an enduring fuel cycle. In the words of the Belgian industrialist Gunther Pauli, "The time has come for human kind not to expect the earth to produce more, but rather to do more with what the earth already produces."

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# Editorial Commentary on the Specific Papers of the Panel Session

Carl E. Walter

## Peter Beck on "Nuclear Energy in Context of World Long-Term Energy"

Peter Beck's presentation had a clear message for those concerned with nuclear power. That message has several thrusts:

- There are almost certainly more remaining fossil resources at affordable prices than those presently considered to be economically available.
- The price of oil is not related to its cost of production, thus it does not follow that its price will rise if a technologically more difficult production method is employed. In fact, the apparently random variation of oil prices with time is only a function of political arrangements that are convenient to the owners of the known oil reservoirs, and subject to strong political influences.
- The attitude of the nuclear power bourgeois community must become more proletarian if nuclear power is to become acceptable to the public. Historically, advocates of nuclear power have not been objective in their appraisal of competing energy sources.

Realistically, the only reasons for choosing to stop using fossil resources in the next fifty years, at least, must be based on other considerations such as the effect of air pollution, acid rain, and GHG emissions.

## Helena Chum on "Two Decades of Progress in Research, Development, and Commercialization of Renewable Energy"

Helena Chum provides the status and the potential for the renewable energy technologies in their "next generation" in terms of their future cost of electric power. Current costs of electricity from these technologies are higher than the cost of electricity from fossil fuel (and some nuclear) plants. Electricity from next-generation solar technologies are not forecast to be competitive, however electricity from geothermal, biomass, and wind may become competitive. She includes land area requirements for some of these technologies to meet U.S. future electricity needs. It appears that these technologies are considerably less land intensive than is the common perception. It is not clear, however, that the cost and land area data include the necessary energy storage subsystems that would be used in conjunction with the technologies that by themselves can supply power only intermittently.

## Steve Fetter on "Climate Change and the Future of Nuclear Energy"

Steve Fetter examined the phenomena associated with global warming in a clear, direct manner. He establishes the allowable rates of emission of GHG in the future and the timing that is required for phasing in these rates. Near-term reductions in GHG would be costly and ineffective. What is required, is a long-term approach that replaces fossil fuels by non-emitting sources beginning up to 20 years from the present. Whether global warming does in fact result from these emissions, he points out that the anthropogenic increase in $CO_2$ concentration in the atmosphere must be seriously considered. In the face of the complexity of climate modeling, we can not afford to ignore the possible consequences of disregarding this issue.

He states that the most urgent need is to initiate now an R&D effort to remove the obstacles to using fission, solar, decarbonized coal, biomass, and wind. Of these, fission is the most highly developed and the only one currently used on a large scale However, fission is faced with adverse public reaction to its safety, cost, waste disposal, and possible use of materials for nuclear weapons. The other sources mentioned above suffer from anticipated high cost, limited areas of application, and lack of mature technology. Current U.S. budgets for fission R&D are too low. The budgets for all these non-emitting sources should be increased significantly. The recent report to the President by PCAST proposes future budgets that are also too low. Because of increasing energy use in the future and the need for substantial reductions in emissions, fission is the most likely source to meet the challenge. Nevertheless, a balanced R&D program that includes **all** the non-emitting sources mentioned above needs to be vigorously executed. In Steve Fetter's words: "We are not smart enough to pick sure winners, and the stakes are too high to rule out any major alternative."

Steve echoes the theme that Peter Beck presented relative to the arrogant stand of fission advocates with respect to the issues confronting the use of nuclear reactors. He suggests areas of investigation for fission R&D. A major goal of this work should be to develop reactor designs that are incapable of producing off-site fatalities.

## Bill Sutcliffe on "Proliferation Concern With Nuclear Power"

Bill Sutcliffe discussed the potential for proliferation of nuclear weapons resulting from the distinct differences between the threats of diversion and theft of nuclear material from the power reactor fuel cycle. He expects there will be less motivation for nuclear weapons in the future because of increasing interdependencies in the world and because technology advances will likely make the use of nuclear weapons less attractive. Theft of nuclear material for making a nuclear bomb will continue to be a threat from terrorists. Theft merely for use as a means to spread radioactivity will become a less effective terrorist device as the public becomes more realistic about the effects of radiation.

## Marion Thompson on "Fast Reactor Fuel Cycle"

Marion Thompson presented sound arguments for continued development and demonstration of the ALMR, an advanced fast reactor design. The design utilizes metal fuel and relies on integral fuel recycling to achieve essentially complete utilization of the energy content of uranium "in the ground" and in currently problematical inventories of depleted uranium resulting from uranium enrichment for LWRs and other uses.

Separated pure plutonium does not occur at any time in the fuel cycle described and plutonium is always in a secured environment. No public road transportation of attractive nuclear materials is envisioned. There is no spent fuel to be disposed of. Most of the waste from the process has a half-life of the order of 30 years. It contains no actinides. Therefore the criteria for geologic disposal become substantially less demanding than for spent fuel.

Marion Thompson, a Principal Investigator in the referenced EPRI study, reviewed the EPRI report conclusion that fast reactors are likely to become economically competitive with once-through LWRs by 2035, and pointed out that development, demonstration, and licensing efforts should precede this date by perhaps three decades. Studies conducted to date indicate that the ALMR design is passively safe and depends on no human intervention for safety.

## Sam Pillay on “Back End of an Enduring Nuclear Fuel Cycle”

In his philosophical presentation, Sam Pillay argues for an ethically responsible approach to designing the nuclear fuel cycle. It is indeed amazing that greater attention has not been paid to this aspect of what has been a major national dependence on nuclear power. He particularly emphasizes the back end of the fuel cycle and suggests that a number of MRS facilities be constructed to accommodate spent fuel until the political climate and fuel cycle technology favors the extraction of fertile and fissile material contained in spent fuel. Doing so will sustain the energy resource for an enduring nuclear fuel cycle.

# Closing Commentary on the Panel Session

## Carl E. Walter

Together, the panel covered a broad area of issues related to the generation of electricity. There do not appear to be disagreements among the panel members on technical issues. Fossil energy resources (and uranium and thorium resources) may greatly exceed the amounts currently considered by most resource analysts to be available. This conclusion results from continuing improvements in resource exploration and extraction technology and in the case of oil, lack of a technical relationship between the low cost of producing oil and its inflated price.

From the standpoint of resource depletion, there may be no need to develop better technologies to produce electricity. Development appears to be indicated from other standpoints, e.g., global warming, environmental impacts, energy security, economics, and ethical consideration of the future world population.

There are strong indications that the world is undergoing a warming trend, and this trend appears to be related to the GHG, e.g., carbon dioxide, emissions associated with burning fossil fuels. The phenomena involved are so complex that even the sophisticated models and computer systems in use today can not be expected to predict the future climate reliably. Although there is no certainty that, indeed, man-made GHG emissions are responsible for the observed temperature increase, can we afford to take a chance? The panel members generally agreed that development of non-emitting technologies should be vigorously pursued, in order to be prepared to substantially change the current rate of GHG emission, should that become necessary. Independent of the global warming issue, attention should be given to elimination of acid rain and air pollution resulting from the use of fossil fuels.

Nuclear power is the most advanced and widely used non-emitting technology. We should ensure its availability for rapid expansion in the future. The long-time constants associated with technology developments and their applications and the residence time of GHG in the atmosphere make it imperative that appropriate actions be initiated now. Failure to do so could result in there being no technology solution available when it is needed early in the next century.

Helena Chum's overview of the renewable energy technologies certainly wets our appetite for more information on these technologies. It behooves the nuclear power community to study the renewable technologies in sufficient system and technology detail to enable an accurate assessment of the relative standings of these technologies with respect to nuclear power. In-depth introspection relative to the issues surrounding the use of nuclear power must take place and an honest consideration must be given to the relative value of nuclear technology and other energy technologies. Above all, it appears that the nuclear community must exhibit greater tolerance toward those who question the value of nuclear power. To paraphrase Peter Beck, the nuclear community has taken on the Marie Antoinette air—"Let them eat cake." Steve Fetter appears to see the same image. Nuclear advocates are now **twice warned and would do well to take heed**.

Funding for R&D of energy technologies is considerably less than it should be to meet the possible challenge of global warming and the likely loss of energy security in the future. Even the increased amounts recommended by PCAST fall short, and the distribution of the inadequate total amount among technologies is inappropriate. Fission power, the most commercialized technology at hand is seriously underfunded, but fusion power, not a likely contender even in the far future, is relatively overfunded.

Proliferation of countries having nuclear weapons and diversion or theft of material from the nuclear fuel cycle are issues of continuing concern– issues that must be controlled at all times. Bill Sutcliffe points out that future improvements in MC&A, availability of other than nuclear weapons of mass destruction, and greater interdependence among nations will decrease the attractiveness of a nuclear weapon capability. These factors will reduce the weapon risk of the nuclear fuel cycle. Application of safeguards and physical protection will continue to provide security for the enduring nuclear fuel cycle.

A way to reduce the weapon risk and simultaneously improve on a number of other objectives of the nuclear fuel cycle is to utilize the fast reactor / fuel recycle system discussed by Marion Thompson. Use of the ALMR solves the spent fuel problem because there isn't any! This avoids placing any significant amount of fertile or fissionable actinides in geologic repositories for possible future weapon use and makes their design for high-level waste much simpler because the half life of the waste is orders of magnitude shorter. Recycling the fuel utilizes non-aqueous processes that do not produce, at any time, pure separated plutonium, thus discouraging weapon interest.

The ALMR design that was being developed in the U.S. is passively safe, and given an unobstructive licensing process, the cost of electricity is less than 4 cents / kWh. In short, it appears to be the best nuclear fission technology known. Uranium enrichment is not required, depleted uranium is not created, and on the contrary, existing inventories of depleted uranium become a valuable energy stockpile—an asset instead of a liability. The ALMR design is ethically correct.

Why continue R&D on LWRs that do not have these superior attributes of the ALMR? Because a long transition period will be required to initially fuel these reactors (from LWR spent fuel**), it is essential that R&D and demonstration of the fast reactor begin immediately**. This recommendation is not necessarily in disagreement with Steve Fetter, who considers the price and availability of uranium as the only motivation for a fast reactor. He supports R&D on nuclear fuel cycles that minimize weapon risk and on alternative waste disposal. The ALMR fast reactor does that. By resuming now the R&D that was recently discontinued, advantage can be taken of existing expertise and infrastructure. This may not be true if one waits until 2005 as suggested by Marion Thompson, or 2030 as suggested by Steve Fetter.

Steve Fetter's suggested goal of fission R&D that there be no off-site fatalities is admirable, but a goal that is not met by many (any?) other technologies. Fast reactor systems can be designed to be sufficiently safe to meet reasonable risk criteria that are also applied to other energy technologies. We disagree with Steve's statement that there is no reason to fund research on fast reactors at the time being. As the paper by Marion Thompson shows, a fast reactor design can meet all the objections to fission energy: safety, cost, waste, and material diversion resistance. R&D on this fast reactor design that neatly solves the waste and spent fuel issues that LWRs cannot, should not be put off. Doing so, places an unnecessary constraint on successfully addressing all the issues facing wider use of fission technology which Steve agrees is needed.

The Panel Session was well attended, and audience participation, in the form of questions showed interest and general agreement in the materials presented. We hope that these Proceedings will provide a lasting basis for continued investigation of the merits of an enduring nuclear fuel cycle in the context of competing technologies.

# Curricula Vitae of the Panel Members

## Peter W. Beck

Associate Fellow
Royal Institute of International Affairs (RIIA)
London, England

Peter Beck is the author of a book *Prospects and Strategies for Nuclear Power* published in 1994. He is a member of a working group on internationally monitored storage of nuclear spent fuel. He advises the Oxford Institute for Energy Studies on the longer-term future of world oil

After graduation as a chemical engineer from the Imperial College of London University, Peter Beck joined the Shell Group in 1945. After almost 40 years with Shell working in the areas of research, supply, manufacturing, and planning, he retired from his position as Planning Director of Shell UK, Ltd. in 1984. He was an original member of the Steering Committee of the Energy & Environment Programme of the RIIA from 1985 until 1994, and has been active in matters relating to business planning and strategy as Chairman of the Strategic Planning Society in UK and subsequently as President of the European Strategic Planning Federation.

Peter Beck is a Fellow of the Institute of Chemical Engineers and a Charter Engineer. He has published articles and lectured widely on subjects related to the practice of strategic planning, energy policy, and the futility of much of energy forecasting.

## Helena L. Chum

Director, Center for Renewable Chemical Technologies and Materials
National Renewable Energy Laboratory
Golden, CO

Helena Chum is responsible for the development of renewable chemical energy and environment technologies and assisting in their commercialization. She has a B.S. in Chemistry (1968) and a Ph.D. in Physical Chemistry (1972) from the University of Sao Paulo, Brazil where she was Assistant Professor of Physical Chemistry until 1979 when she joined what is now the National Renewable Energy Laboratory.

She is qualified in electrochemistry and analytical chemistry as applied to biomass and wastes; electrochemistry of molten salts and fuel cells using methanol and carbonaceous fuels, environmental chemistry using solar technologies, and energy and environment policy analysis. Currently, she manages R&D projects on conversion of biomass and a variety of organic wastes into fuels and other materials. Her activities include the development of biomass standards and analytical methods as well as collaboration with the International Energy Agency on biomass and hydrogen.

She is co-inventor in several patents for recycling plastics. In 1995, she contributed to the development of an action plan for solar, wind, and biomass energy development in Brazil. She is a member of the American Chemical Society, Electrochemical Society, American Association for the Advancement of Science, among others.

## Steven Fetter

Associate Professor
University of Maryland
College Park, MD

Steve Fetter is associate professor in the School of Public Affairs at the University of Maryland, and writes on technical aspects of security and environmental policy. He is a member of the National Academy of Sciences' Committee on International Security and Arms Control, a fellow of the American Physical Society, and has consulted to the U.S. government.

He has been special assistant to the Assistant Secretary of Defense for International Security Policy; Council on Foreign Relations Fellow at the State Department; Visiting Science Fellow at Stanford University's Center for International Security and Arms Control; Postdoctoral Fellow at Harvard University's Center for Science and International Affairs; visiting scientist at MIT's Plasma Fusion Center; and Arms-Control Fellow at Lawrence Livermore National Laboratory.

Steve Fetter has a B.S. in physics from MIT, and a Ph.D. in energy and resources from the University of California, Berkeley. His articles on policy related issues have appeared in *Science*, *Nature*, *Scientific American*, *International Security*, *Science and Global Security*, *Bulletin of the Atomic Scientists*, and *Arms Control Today*. He has contributed chapters to fifteen edited volumes on arms control and is author of the book, *Toward a Comprehensive Test Ban*.

## William G. Sutcliffe

Senior Physicist
Lawrence Livermore National Laboratory (LLNL)
Livermore, CA

Bill Sutcliffe is a Senior Physicist at Lawrence Livermore National Laboratory dealing with nonproliferation of weapons and nuclear fuel cycle issues. He has a B.S. in Mathematics (1960) from the University of Michigan and a Ph.D. in Theoretical Physics (1969) from the University of Delaware where he was a NASA fellow. He was a Navy officer and taught mathematics, physics, and shielding under Admiral Rickover.

At LLNL, he has modeled neutron cross sections, developed large hydrodynamic and radiation transport computer codes, and led nuclear waste studies involving uncertainty, risk, and decision analyses. He has analyzed the requirements, capabilities, limitations, and costs of atomic weapon systems, weapon material supply and demand issues, and impacts of arms control proposals.

Bill Sutcliffe was a Senior Fellow at LLNL's Center for Security and Technology Studies dealing with nonproliferation of atomic weapon technology and materials and the disposition of fissile materials. He organized and managed a comprehensive plutonium disposition project for the Department of Energy, and consulted for the National Academy of Sciences' Committee on International Security and Arms Control on the study, *Management and Disposition of Excess Weapon Plutonium*.

## Marion L. Thompson

Consultant
Fremont, CA

Marion Thompson has 37 years experience with General Electric Co. in nuclear safety, fuel fabrication and R&D, chemical processing, and plutonium facility startup, operation, and decommissioning. His expertise includes technical and economic evaluation of fuel cycles and application of systems engineering to achieve quality production and reliability. He received a B.S. in Material Science Engineering from California State University (1971).

At GE, he was a major participant in major industry/national laboratory task forces that interfaced with the National Academy of Sciences on actinide recycling in advanced fast reactors and on utilization of excess weapon plutonium. He was commended for contributions to plutonium laboratory decommissioning, actinide recycle activities, and excess weapon plutonium disposition studies. He is the author of several publications.

Marion Thompson was a principal author of an EPRI report on the economic potential of plutonium compared to uranium. He now consults for Lockheed-Martin Co. on waste processing and Los Alamos and Oak Ridge National Laboratories on MOX fuel issues in the disposition of excess weapon-grade plutonium. He is a certified Manufacturing Engineer/Technologist and a member of Robotics International of the Society of Manufacturing Engineers.

## K. K. S. (“Sam”) Pillay

Senior Staff Member
Los Alamos National Laboratory
Los Alamos, NM

“Sam” Pillay has 30 years of nuclear experience with special emphasis on process chemistry. He has a Ph.D. in Inorganic and Radioanalytical Chemistry from Pennsylvania State University. His present work is in process chemistry and safeguards of nuclear materials radioactive waste management, and arms control.

Sam Pillay worked at Argonne National Laboratory, State University of New York, and Pennsylvania State University. At Los Alamos since 1981, he has developed technologies for international safeguards relevant to nuclear materials processing and participated in various international groups on nuclear materials processing, waste management, weapon proliferation, and related issues.

He is a fellow of the American Institute of Chemists and the American Nuclear Society, and an active member of the American Chemical Society, Institute of Nuclear Materials Management, Health Physics Society, American Association for the Advancement of Science, American Society for Testing Materials, and the New York Academy of Science. He has published extensively and is currently an Associate Editor of the *Journal of Nuclear & Radioanalytical Chemistry*. He reviews papers for *Analytical Chemistry*, *Nuclear Applications*, *Nuclear Science & Engineering*, *Science & Global Security*, and *the American Chemical Society’s Advances in Chemistry Series*.

# Addresses

Peter W. Beck
The Royal Institute of International Affairs, London
Stone House, The Green, Frant
East Sussex TN3 9DN, UK
e-mail: PETER_BECK_FRANT@msn.com
Tel: (01892) 750200, Fax: (01892) 750750

Helena L. Chum
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
e-mail: chumh@tcplink.nrel.gov
Tel: (303) 275-2949, Fax: (303) 275-2905

Steven A. Fetter
University of Maryland, School of Public Affairs
College Park, MD 20742-1821
e-mail: sfetter@puafmail.umd.edu
Tel: (301) 405-6355, Fax: (301) 403-8107

Robert A. Krakowski
Los Alamos National Laboratory
Los Alamos, NM, 87545
e-mail: krakowski@lanl.gov
Tel: (505) 667-5863, Fax: (505) 665-5386

K. K. S. Pillay
Los Alamos National Laboratory
Los Alamos, NM 87545
e-mail: s_pillay@lanl.gov
Tel: (505) 667-5428, Fax: (505) 667-7966

William G. Sutcliffe
Lawrence Livermore National Laboratory
P. O. Box 808, L-175, Livermore, CA 94551
e-mail: sutcliffe1@llnl.gov
Tel: (925) 422-3986, Fax: (925) 422-6434

Marion L. Thompson
44850 Parkmeadow Drive
Fremont, CA 94539
e-mail: mariont@ix.netcom.com
Tel: (510) 657-0789, Fax: (510) 353-1686

Carl E. Walter
Lawrence Livermore National Laboratory
P. O. Box 808, L-125, Livermore, CA 94551
e-mail: walter3@llnl.gov
Tel: (925) 422-1777, Fax: (925) 423-8164